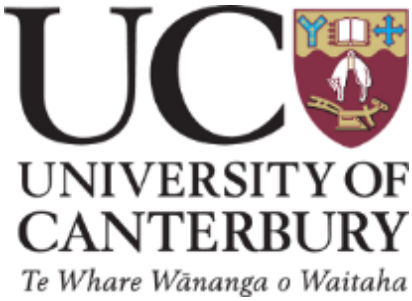
The effects of root pruning on the growth, physiology and monetary value of *Quercus virginiana* and two species of *Acer*.

A thesis
submitted in partial fulfilment
of the requirements for the
Degree of
Doctor of Philosophy
in Forestry
by
Andrew R. Benson



School of Forestry

University of Canterbury

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Remember the river

Abstract

The urban environment in which we live is ever-changing and subject to continued modification to accommodate population growth and to meet modern engineering standards. Within this ever-changing environment, land disturbance and ground modifications are commonplace, which can place nearby urban trees at risk of root damage or root removal, the effects of which can result in physiological stress, growth retardations, reduced life expectancy and increased mortality.

In many regions of the world, the constraints placed upon urban trees by land modifications has prompted the implementation of a range of statutes, best practice documents and local legislations, to afford protection to urban trees, particularly during construction work and development. These documents often contain specific recommendations for tree protection methods and root care practices, informed by the findings of a small pool of research outputs.

The objectives of this thesis were to test the validity of some of the current best practice recommendations relating to tree protection, root pruning and root care practices. In particular, a novel allometric approach to root pruning methods is proposed. In three experiments exposing trees to different types of root severance treatments, the measured diameters of individually severed roots were used to estimate root cross-sectional area. Combined severed root cross-sectional areas for each tree were divided by the trunk cross-sectional area at a given height (x) above ground level, to produce an allometric Area Ratio; $Ar_{(x)}$.

Experiments were carried out in New Zealand, to investigate the effects of increasing root removal treatments on growth (trunk diameter increase, leaf area and new shoot elongation) and physiology (stomatal conductance and chlorophyll fluorescence) of 100 *Acer palmatum* 'Bloodgood' Thunb and 19 *A. negundo* L. Trenches were established 30 cm from the tree base on one (T1) two (T2), three (T3) or four (T4) sides of the trees, plus control (no trenches).

In Florida, USA, two experiments were undertaken using *Quercus virginiana* Mill. The first, was a test of the current tree protection zone (TPZ) principles. Mature trees (n=18) were exposed to five root pruning treatments consisting of a circular trench around each tree, plus control. Trenches were established with radial offsets from the tree base between 3 and 15 times the trunk diameter in increments of three (3x, 6x, 9x, 12x and 15x), plus control (no trenches). The same morphological and physiological responses as the New Zealand study were investigated, with the inclusion of pre-dawn leaf water potential data.

The second Floridian experiment simulated utility trenching (linear root cutting), again using mature *Q. virginiana* (n=31), with treatments consisting of a ≈ 10 m long liner trench offset from the tree base at either twelve (12x), six (6x) or three (3x) times the trunk diameter plus control (no trenches). Morphological and physiological data were investigated as response variables in the same way as the first Floridian experiment.

In addition to the physiological and morphological response data, each tree was appraised and given a monetary value prior to and several months after root manipulation using four different tree valuation methods (CTLA trunk forumula method 9th Edition (CTLA), the Revised Burnley Method (Burnley), the Helliwell Method (Helliwell), and the Standard Tree Evaluation Method (STEM)). Response data following root removal were expressed as a pecentage change in value (Δ value %). The purpose of this investigation was to ascertain whether root removal had any effect on the monetary value of urban trees, and to compare the effectiveness of each of these methods for this purpose.

Results of this work indicated that a tree protection zone radius of 12 times the trunk diameter at breast height (≈1.4 m), was insufficient to protect *Q. virginiana* from short-term physiological stress effects during the summer growing season immediately following root severance. Although it was sufficient to avoid sustained water stress symptoms during the first summer growing season after root removal, as well as negative effects on above-ground growth. No significant negative effects were recorded when roots were severed in circumferential trenches with a radius of 15 times the trunk diameter at 1 m.

Severing roots in utility-type trenching made at a distance from the tree base equivalent to three times the trunk diameter at breast height (3x), resulted in sustained water stress symptoms 14 months following root removal, where other treatments (6x and 12x) showed signs of recovery.

The allometric variable ($Ar_{(x)}$) proved to be a reasonably reliable (R^2) and significant (p value) predictor of both physiological and morphological responses, although varied among species / location. Negative effects on above-ground growth for *A palmatum* 'Bloodgood' and *A. negundo* trees, have the potential to arise when the total combined cross-sectional area of severed roots exceeds 22% and 27% of the trunk cross-sectional area at 1.4 m respectively (assuming radial uniformity of the root and trunk cross sections).

The results revealed a general trend towards greater loss in monetary value (Δ value %) with increasing root removal intensity for all methods for one or more treatment types. Values appraised using the CTLA and Burnley methods showed a greater sensitivity to changes in the amount of root loss, owing to the fine scale resolution within a rigid framework of descriptors in the awarding criteria. STEM and Helliwell were generally insensitive to root removal treatments. Linear mixed model analyses using four independent variables (maximum severed root diameter, % tree protection zone removed, total number of severed roots, and $Ar_{(x)}$) revealed that % tree protection zone removal was the best performing tool for predicting percentage loss in value following root removal.

The research outputs of this work have a practical application to assist practitioners in achieving an optimum standard of tree care during ground alterations. Although trees may behave differently between species and age classes, the tree protection zone principles have not previously been empirically tested. By observing how *Q. virginiana* responded to the circumferential root removal treatments, this thesis provides an empirical platform on which to encourage practitioners to extend tree protection zone radii to 15 times trunk diameter at 1 m, as a minimum, if the physiological effects of water stress are to be avoided in the short-term.

In acknowledgement again that responses may vary between species and location, the observations made when *Q. virginiana* roots were severed in linear trenches, again adds a level of empirical robustness to guidelines and best practice texts relating to trenching offsets. Where the work of others has found that linear root cutting closer than three times trunk diameter at breast height can negatively affect tree stability, the results of this work indicate that severing roots at the same distance (three times trunk diameter), results in sustained water stress symptoms. Those symptoms were alleviated when the trenches were made at a distance equal to six times the trunk diameter at breast height (equating to 24.10% of a tree protection zone prescribed using a 15:1 ratio of trunk diameter). These findings would indicate that severing roots closer to the tree than a distance equal to six times its trunk diameter is not recommended.

Whilst the results add valuable information to a limited pool of knowledge on the effects of root loss, further research using large numbers of different species exposed to the same or similar types of root removal would be advantageous, and necessary to make more robust and generalisable guidelines to the industry. Particularly as this relates to the findings on tree protection radii, where the investigation was limited by the number of available trees and consequently had a low number of replicates. Furthermore, since all of the investigations carried out in this thesis were constrained by time, the temporal effects of root loss on the investigated species were not thoroughly understood. The findings of the linear root cutting experiment would suggest that there is physiological and morphological recovery in *Q. virginiana* in the 6x and 12x treatments after one year. A similar behaviour would be expected when roots were severed circumferentially, and this understanding would further help inform decisions pertaining to tree protection zone recommendations.

Whilst the $Ar_{(x)}$ variable was a significant predictor of the response variables, the unexplained variance in the models was, in some instances, greater than that which was explained. Furthermore, the relationships in each instance were linear, i.e. no curvature in the response was observed. The absence of curvature and occasionally weak (yet significant) relationships between $Ar_{(x)}$ and response, as well as the variation in response between species, precluded its use as a tool to clearly prescribe a broadly generalisable root pruning 'threshold' at which no further root removal should occur. Although the method is more robust than a fixed diameter threshold when accounting for cumulative root loss, the practicalities of its application in a commercial sense would be onerous and time consuming to a practitioner, and a trunk diameter-defined offset at which root loss should be avoided (i.e. no closer than six times trunk diameter at breast height), remains the most suitable means of accounting for cumulative root loss in a practical way.

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Chapter 1: Introduction

1.1 The urban forest

In recent times, cities around the world have developed close relations with nearby forests (Konijnendijk, 2018), which has subsequently resulted in the forest being regarded as part of the wider urban green structure (Konijnendijk, 2018). The term 'urban forest' is commonly used to describe trees - both publicly and privately owned - along streets, in parks and gardens as well as areas of woodland (Konijnendijk et al., 2006; Konijnendijk van den Bosch et al., 2017). In the broadest sense, it may include any kind of woody plant vegetation growing in and around human settlements. 'Urban forestry' relates to the cultivation and management of urban trees for the physical, social and economic well-being of urban society (Ranasinghe and Hemakumara, 2018).

1.1.1 Ecosystem services

Urban forests are a significant and increasingly valuable component of the urban environment (Dwyer et al., 1992). Apart from the obvious aesthetic values, such as leaf colour and flowering, urban trees offer a range of ecosystem services and contribute to biodiversity goals (Morgenroth et al., 2016). Ecosystem services are defined as the direct and indirect contributions of ecosystems to human well-being (Brouwer et al., 2013). They are broadly categorised into regulating, cultural, supporting and provisioning services (Samson, 2017).

Regulating services are those which have a regulatory effect on the environment. For example, impermeable surfaces in urbanised areas often result in large volumes of surface water runoff (Voter and Loheide, 2018). Trees can help intercept rainfall, attenuate storm water flows, filter pollutants (Stovin et al., 2008) and reduce nitrogen eutrophication (Denman et al., 2006). Urban trees play a major role in sequestering atmospheric carbon dioxide (Nowak and Crane, 2002).

They contribute to improved urban air quality by reducing smog and trapping airborne pollutants (Brack, 2002; Nowak et al., 2006; Ozdemir, 2019). Summer 'heat islands' in urban areas are created through high solar radiation absorption by urban surfaces such as buildings, roads and pavements, and temperatures can be elevated by up to 5 degrees Celsius in comparison to surrounding rural settings (Akbari et al., 1990; Akbari et al., 2001). Trees can regulate temperature and help mitigate the 'heat island effect' through shade and evaporative cooling (Souch and Souch, 1993; Thom et al., 2016; Wang and Akbari, 2016).

Cultural services are those which are provided through interactions with people. For example, urban trees provide financial benefits to building owners by reducing air conditioning costs by regulating atmospheric temperature (Akbari, 2002). They can have a substantial impact on the health and wellbeing of community residents (Nowak et al., 2001). Treed environments help to reduce violence and aggression in residential areas (Kuo and Sullivan, 2001). Window views of greenspaces and natural surroundings can improve rehabilitation times in convalescing patients (Raanaas et al., 2012). Roadside trees help to reduce driver fatigue (Neale, 1949) and physiological stress in motorists (Parsons et al., 1998). Trees can influence motorist speed, have calming effects on traffic (Godley et al., 1999; Naderi et al., 2006) to reduce the number of motor vehicle accidents (Naderi, 2003; Van Treese Ii et al., 2017). Trees can help to reduce vehicle noise (Margaritis et al., 2018) as well as incidences of mental illness associated with that noise (Dzhambov et al., 2018). Treed and forested areas add to property values (Tyrväinen, 1997; Tyrväinen and Miettinen, 2000) and contribute to positive perceptions of community character (Wolf, 2006). A single street tree may increase median house prices by as much as AUS$16,889 (NZ$17,957) (Pandit et al., 2013), and home-buyers may be willing to pay up to 3.73% more for a house in a street which has canopy cover targets (Plant et al., 2017).

Supporting services are those that are necessary for the production of all other ecosystem services. Their impacts are either indirect or occur over a very long time, in contrast to other service types, which have relatively direct and short-term impacts (Milliken, 2018). In urban ecosystems, an important supporting service is the provisioning of habitat, since trees play important roles in supporting various species of fauna in this regard (Germaine and Wakeling, 2001; Melles et al., 2003; Nielsen et al., 2014).

Provisioning services are those which yield products with associated benefits to society, such as fruiting trees which produce an edible crop to city residents (McLain et al., 2012; Reed et al., 2017; Hurley and Emery, 2018). Efforts to establish crop-bearing trees in urban communities can be a valuable strategy to address poverty and add resilience to sustainable food practices (Clark and Nicholas, 2013). In some impoverished regions of the world, urban trees may also provide valuable sources of combustible material and timber for construction efforts (Shackleton et al., 2015).

When considering the services provided by an urban forest, size and number of trees play import roles (Dobbs et al., 2011). A larger tree by virtue of its size will intercept greater volumes of rainfall and surface water runoff than a small tree. It will cast more shade, trap more pollutants, and sequester more carbon and these effects are multiplied with increasing numbers. The same is true of cultural, supporting and provisioning services, since a greater number of larger trees will clearly contribute more positively than fewer, or smaller trees.

Many of these ecosystem services are related to healthy leaf area (Nowak and Dwyer, 2007; Nowak and Aevermann, 2019), and so large, healthy trees with greater leaf area will play greater roles in ecosystem service provision. In recent times, various methods have been developed to quantify the value of these services, to convey the information in meaningful ways to decision makers and stakeholders alike (Nowak, 2018). One such approach is the i-Tree Eco software (The i-Tree Development Team, 2019), which uses measured tree dimensions in combination with local climate and pollutant information, to provide quantitative estimates of ecosystem services for individual trees and tree populations, based on the Urban Forest Effects Model (UFORE) (Nowak and Crane, 2000; Nowak, 2008). Establishing the link between healthy canopy leaf area and ecosystem service provision, illustrates the need to maintain a healthy, functioning and mature urban forest. Effectively managing and protecting urban trees is essential for the longevity of the urban forest and the plethora of benefits which it provides (Vogt et al., 2015). A key component of this is ensuring that correct and appropriate tree management decisions are made.

1.1.2 Urban forest management: Challenges and conflicts

Those responsible for managing urban forests face highly complex challenges and rapidly changing urban demands (Gustavsson et al., 2005). Urban sites can prove to be harsh environments for tree growth, characterised by limited growing space, high levels of pollutants and adverse climatic conditions (Konijnendijk et al., 2006). Urban trees are also exposed to an array of anthropogenic behaviours, and vandalism is a definite contributor to the mortality of newly planted trees (Black, 1978; Nowak et al., 1990). Once established, trees in the urban environment are continually under threat from urban development (Smith et al., 2009), utility installation and repair (Sánchez et al., 2013), the need for improved transport infrastructure (Chi, 2012; Duranton and Turner, 2012) and requirements for the hardscape to meet modern engineering requirements (Jim, 2003; Chen et al., 2014). To this end, conflicts begin to manifest between trees and infrastructure (Koeser et al., 2013), largely due to spatial constraints in tree growing environments (Wong et al., 1988; Francis et al., 1996; Kadir and Othman, 2012). Such conflicts may take the form of damage to pedestrian and vehicular transport infrastructure (pavements and roads) through interactions between woody roots and hard surfaces (Nicoll and Armstrong, 1998; Morgenroth, 2008; Kadir and Othman, 2012). Infrastructure damage caused by trees forms a sizable economic problem. In Hanover, Germany, up to half of 2,881 surveyed street trees were found to be causing damage to hardscape (Reichwein, 2002). In Manchester, England, 30% of street trees caused damage to pavements, and 13% caused damage to kerbs (Wong et al., 1988). It has been estimated that tree-related damage to pavements can cost US$70 million annually in some parts of the USA (McPherson, 2000) and up to CDN$2.4 billion in parts of Canada (Rajani, 2002). In Hamilton, New Zealand, it is estimated that tree-related infrastructure conflicts represent annual expenditures to effect repairs in the order of NZ$100,000 (Hamilton City Council, 2018a).

The costs associated with construction damage during pavement or infrastructure repairs may also be expressed in terms of depreciation of the tree asset. The value of trees can be ascribed using one of any number of tree appraisal methods (Ponce-Donoso et al., 2017), which award points based on tree attributes - such as overall health and condition - and then, through mathematical operations, convert the points to a monetary value (Watson, 2002). In Milwaukee, USA, annual depreciations of the city's tree asset (approximately 200,000 trees) due to construction-related damage has been estimated to be in the order of US$792,100, either due to mortality ($US270,600) or reduced tree condition (US$521,500) (Hauer et al., 1994).

Roots may also interact with building foundations, either directly, where the physical increase in size of growing roots causes the structure to move through mechanical pressure (Day, 1991), or indirectly, by influencing soil moisture volumes of reactive, or shrinkable soils (Lawson and O'Callagahan., 1995). Such soils often have a high clay content, made up of layers of silicate or alumino-silicate minerals. The interlayer space is often charged, due to the polar nature of the mineral ions within the clay (Prikryl, 2006). Hydration of the interlayer space occurs during periods of water abundance, when water is 'trapped' due to opposing charges of the clay cations and the oxygen of the water molecule, causing the clay to expand (Laird, 1997), and the soil to 'swell'. Conversely, during periods of reduced water availability, water is depleted and the soil 'shrinks'. It is this soil shrinkage which is often influenced by trees, through transpiration and extraction of soil water by the roots (Day, 1991; O'Callaghan, 2005). This shrink-swell behaviour can give rise to subsidence and heave (respectively), which can cause building foundations to move. The problem is particularly common in England, where annual tree-related subsidence claims may be in the order of £390 million (The London Tree Officers Association, 2008).

Utilities (such as water and sewer pipes) may also be damaged through root interactions. Although roots do not ordinarily penetrate utility pipes or ducts, they are known to exploit existing openings or weaknesses, particularly if the pipe happens to be made from a porous material such as clay (Watson et al., 2014). Once inside, they proliferate into a moist, nutrient-rich environment.

Roots may also damage pipes through anatomical interactions, whereby they become encircled around the pipe which can subsequently break during wind-force loading and / or tree failure, or due to secondary growth (Mattheck and Breloer, 2007a).

These types of conflicts may result in complete tree removal to make way for new hardscape and infrastructure (Morgenroth et al., 2017; Guo et al., 2018; Guo et al., 2019), or to effect repairs and limit future damage (McPherson, 2000; O'Callaghan, 2005). Alternatively, these conflicts may result in the complete or partial destruction of root systems, when below-ground alterations such as utility work (Thomson and Rumsey, 1997) or pavement repair (North et al., 2017) are undertaken in proximity to trees. Removing tree roots can elicit a range of negative effects, including reduced growth (Ferree, 1992; Miller and Neely, 1994; Khan et al., 1998; Wajja-Musukwe et al., 2008; Pretzsch et al., 2016) and vitality (Hauer et al., 1994; Watson, 1998), reduced stability (Smiley, 2008; Ghani et al., 2009; Smiley et al., 2014), impairment of physiological processes (Ferree et al., 1999; Fini et al., 2013b; Wang et al., 2014; Dong et al., 2016), and increased mortality (Hauer et al., 1994). With the link between ecosystem service provision and a healthy, functioning and mature urban forest already established (McPherson et al., 1994), the effects of root loss on tree health and longevity due to urban conflicts, may consequently diminish the value of individual trees and the wider urban forest as a whole.

1.1.3 Managing conflicts

Currently, arboricultural specialists rely on industry standards (Standards Australia, 2009; British Standards Institute, 2012), best management practice (BMPs) documents (Fite and Smiley, 2016), anecdotal evidence and legislation (The Government of the Hong Kong Special Administrative Region, 2015; Auckland Council, 2018) when making tree management decisions that relate to tree preservation. Typically, these documents include specific recommendations relating to tree protection methods, maximum permissible distances at which ground alterations can take place (e.g. how close to the trunk a trench can be made in which roots are severed), root zone encroachment thresholds (e.g. a maximum percentage of viable root zone which can be removed), root pruning specifications and root care practices.

A common component of the BMPs, is the provision of a tree protection zone (TPZ); often defined as the area of ground around a tree, within which it is expected that there are sufficient volumes of soil and roots to sustain healthy tree function and stability. Where root zones are unimpeded (there are no obstructions to lateral root growth), the TPZ area is considered to be circular, and most commonly prescribed with a radius equivalent to 12 times the trunk diameter at breast height (DBH ≈1.4 m).

This approach is commonplace where greenfield-type developments are involved, on large areas of undisturbed ground where trees have uninterrupted root zones. In more confined urban areas, where trees may be planted in narrow grass berms (Jim, 1997) placing them close to land modification (Despot and Gerhold, 2003), root care guidelines may provide specifications for infrastructure-related works, with recommendations for trunk offsets at which ground alterations (such as utility trenching) should not take place (e.g. The City of Regina, 2000; The City of Bellevue, 2009). Other guidance documents provide specifications for individual root pruning thresholds using fixed diameters (e.g. no roots greater than 25 mm in diameter should be severed) (e.g. National Joint Utilities Group, 2007), however this method fails to account for the size of the roots relative to the size of the tree, as well as cumulative root loss. Whilst many regions of the world provide trunk offsets, or encroachment thresholds, the fixed diameter approach has long been established in the arboricultural sector in the Auckland region of New Zealand's North Island, although without empirical support. This approach has now precipitated into Auckland's recent regulatory framework; the Auckland Unitary Plan (e.g. Auckland Council, 2018), where the threshold may range from 35 mm to 80 mm in diameter. Interestingly, the range of values does not reflect tree attributes (e.g. do not sever roots greater than 35 mm in diameter from a small tree or 80 mm in diameter from a large tree), rather it depends upon who is responsible for removing the roots. For example, during utility repairs, the utility contractor may remove roots up to 35 mm in diameter from any size tree with no arboricultural input. However, an arboricultural specialist may remove roots up to 80 mm in diameter during the same operation.

Although the intention of these guidance documents is to provide desirable outcomes for urban trees, whilst meeting the demands of urban development, many of them lack empirical testing (Watson, 1998; Costello et al., 2017). It is critical for arboricultural practitioners to understand the implications of root removal in order to effect desirable outcomes, as these relate to the management of urban trees and the wider urban forest.

1.2 Research opportunity

The aims of this research are to investigate the effects of root loss on urban trees, and to explore an alternative to fixed diameter root pruning guidelines which are commonplace in New Zealand. To do so, a literature review was undertaken (Chapter 2) to ascertain the current state of knowledge and inform the specific research questions posed by three experiments (Chapter 3). Chapter 4 describes a specific method to quantify sapwood area using electronic resistance tomography and Chapters 5 to 8 present the results of the three experiments which exposed trees to different types of root loss, to test current tree protection mechanisms and the recommendations in various guidance documents. Although the numbers and orientations of the trenches were different in each experiment, cumulative root loss of individual trees was accounted for using a novel allometric method, which expresses estimates of the total severed root cross-sectional area as a proportion of estimated trunk area. Changes in tree growth (trunk diameter, shoot growth and leaf area), physiology (chlorophyll fluorescence, pre-dawn leaf water potential, and stomatal conductance), the appearance of reduced vitality (tree condition rating) and changes to monetary value are examined in response to different root removal treatments. The findings are discussed (Chapter 9) in the context of current guidelines and recommendations are made with reference to how these findings can be used to improve current work practices.

Chapter 2: Literature review

2.1 Tree constraints in the urban environment

The belowground environment of urban soils is often inhospitable and restrictive to root growth and can limit tree establishment (Jim, 1993; Grabosky et al., 2002; Layman et al., 2016). Impediments to root system development can be an underlying cause of an array of tree health problems (Patterson, 1977; Ruark et al., 1983; Krizek and Dubik, 1987; Flückiger and Braun, 1997; Kozlowski, 1999). Water and nutrient availability are key to tree survival (Martinez et al., 2013a; Martinez et al., 2013b) and water stress plays a major role in urban tree mortality, especially where pavements, soil compaction, and small planting pits are restrictive to tree growth, and can prevent adequate infiltration into the root zone (Patterson, 1977; Miller and Miller, 1991; Whitlow et al., 1992; Kozlowski, 1999; Pauleit et al., 2002). Rooting restricted by adjacent buildings or roads (Čermák et al., 2000) can reduce stability and increase stress (Hamilton, 1988; Watson et al., 2014).

Once established, it is not uncommon for urban trees to be poorly and repeatedly pruned by homeowners and utility arborists (Close et al., 2001), rendering them irrevocably disfigured and exposing them to negative health effects (Shigo, 1983; Kaiser et al., 1986). This is true both above and below ground, where roots are pruned due to perceptions of damage to infrastructure (Randrup et al., 2001). Furthermore, established trees in roads or parks often have their root systems affected by construction work such as utility installation (Thomson and Rumsey, 1997) or pavement repair (North et al., 2017).

There are many facets to the proper care and management of urban trees and there are many challenges which the practitioner and asset manager must overcome. This review focusses on the management of roots and root systems and investigates what is currently known about the effects of root removal. Additionally, some morphological characteristics of trees and their roots (such as allometric relationships) which are fundamental to the basis of this thesis, will be explored and discussed.

2.2 Root pruning in the urban environment

There are various ways to manage conflicts between trees and infrastructure (Morgenroth, 2008), and whilst the most preferable is through strategic engineering and design (Dockter, 2001), the easiest, and most common 'go-to' approach is to remove the offending tree part responsible for the conflict. In the context of this thesis, the offending part is the root, or roots. Although private trees on property frontages may also be affected, trees growing in road corridors (e.g. in grass berms next to roads and pavements) are those which are most predisposed to root injuries due to infrastructure conflicts, owing to the sharing of limited space for pavements, roads, utilities and other street paraphernalia (McPherson et al., 2001). It is not uncommon for roadside trees to be repeatedly affected by infrastructure repair works in the road corridor (de la Chevallerie, 1986).

Root pruning is an injurious practice whereby offending roots are removed, usually when infrastructure becomes damaged (Hagen, 2001). In urban environments, fine roots develop at shallow depths directly beneath hard surfaces (e.g. pavements), due to favourable growing conditions (e.g. available soil moisture and optimum temperatures) (Wagar and Franklin, 1994; Grabosky et al., 2001; D'Amato et al., 2002) and subsequently cause damage to the hard surface as a result of secondary growth (Nicoll and Armstrong, 1998). Mature trees with well-developed root systems are more likely to damage hard surfaces, and are therefore more at risk of root loss during pavement repair operations (Kopinga, 1994; Nicoll and Armstrong, 1998). Although root pruning is commonly undertaken to remedy the damage (North et al., 2017), because each scenario is unique, precise recommendations specifying the maximum extent of root loss are often absent - although generally, as few roots as possible should be removed (Costello and Jones, 2003). However, in some instances, the root loss required to remedy the damage is extensive, and sufficient to warrant tree removal (Mitchell, 2017; Sandys, 2017).

Roots may also be pruned when new infrastructure is established, and utility trenching is a good example of this. Utility trenching involves making long spans of linear excavations of variable depths and widths, often in the pavement or grass berm to lay new utility pipes or ducts (Rogers et al., 2012), during which roots may be indiscriminately severed (Jim, 2003). Trenchless techniques such as tunnelling, or directional drilling are preferable methods of installing new utilities to avoid root loss (Morell, 1984; Thomson and Rumsey, 1997), although their application may be limited by the availability of underground service plans (Metje et al., 2007). In New Zealand, the Government have committed to providing new internet fibre broadband connections to 1.75 million homes and businesses by 2022 (corresponding to 99.8% of the population), and much of the installation work requires utility trenching (The New Zealand Government, 2019). Whilst provisions exist for the preservation and protection of public and private trees in some parts of the country (McCarrison et al., 2015), other regions are not afforded the same level of protection, and incidences of root losses and tree damage have been recorded (Cadwallader, 2019b).

Guidelines for root pruning vary and are limited by a finite pool of research. Making broadly generalisable recommendations for all circumstances is difficult since the relative tolerances of trees to root removal varies by age, species, tree condition and environmental factors such as soil conditions and water availability (Costello and Jones, 2003). That said, if managed correctly, and root loss is kept to the minimum amounts, trees are often able to tolerate some degree of root pruning (Hamilton, 1988).

2.3 Functions and importance of roots

The primary function of roots is to provide water and solute transport from the soil to the shoots and leaves (Tyree, 2003). Fine fibrous roots and root hairs facilitate absorption of water and dissolved soil minerals, and thus play important roles in photosynthesis (Hamilton, 1988; Day et al., 2010). Water uptake is generally under osmotic control and mineral ion absorption may take place via electrochemical gradients or by means of active transport (Epstein, 1955, 1956). Movement of water and dissolved mineral ions takes place in the xylem tissue of the roots through to other parts of the plant (Biddulph, 1959).

Symbiotic interactions between fine roots and mycorrhizal hyphae effectively increase the surface area of roots in contact with the soil, enabling trees to increase water and mineral ion absorption (Rosling and Sveriges, 2009; Genre and Bonfante, 2010). Of particular importance is the ability of these interactions to increase the availability of phosphorous, which is relatively unavailable in a usable form due to its insolubility. Mycorrhizae have the ability to convert phosphorous into a soluble form thereby making it more available to roots (Watson, 2006).

Carbohydrate reserves play an essential role in all trees (Khan et al., 1998). Large woody tissues at the tree base act as storage organs (Hay and Woods, 1978; Coutts, 1987) and represent a major sink of non-structural carbohydrates (Hartmann and Trumbore, 2016). Non-structural carbohydrates have critical functions in environmental stress recovery (Hartmann et al., 2013; Nardini et al., 2016; Kannenberg et al., 2018) and tree defence (Hillis, 1977; Morris et al., 2016).

Wind-force loading is the largest force to which trees are commonly exposed and can place their trunks and root plates under considerable stress (Niklas and Spatz, 2000; James and Kane, 2008). Roots therefore are an integral component of anchorage and tree stability (Coutts, 1983; Danjon et al., 2005; Dupuy et al., 2005a; Peltola, 2006; Coder, 2010), particularly those structural roots in close proximity to the trunk (the root plate). Interactions between woody roots and the soil - such as viscoelastic damping - enable trees to remain upright and dissipate kinetic energy (James et al., 2006; Mattheck and Breloer, 2007b; Coder, 2010).

2.4 Root system architecture and tree allometry

Allometry is the study of size and its biological consequence (Niklas, 2004). Specifically, it is the scaling relationship between the size of a body part and the size of the body as a whole. Often, one readily measurable body part is used to estimate another, less accessible part. For example, some of the earliest work investigated the relationship between body weight and brain size for 47 different species of warm-blooded animals (22 mammals and 25 birds) (Snell, 1892), or the ratio between different anatomical features of crabs (Huxley, 1924; Miller, 1973).

The relationships among tree parts are often highly correlated because of structural and physiological requirements among different plant parts (Bartelink, 1996), and allometry is frequently used to describe these relationships. For example, trunk diameter is regularly used to explain differences in leaf area (Vertessy et al., 1995; Bartelink, 1996; Peper et al., 2001; Gould and Harrington, 2008), biomass (Bond-Lamberty et al., 2002; Bolte et al., 2004; Youkhana and Idol, 2011; Mugasha et al., 2013) and carbon stocks (Beets et al., 2012). These types of relationship are of particular importance to forest managers, who need to understand expected merchantable timber yields (Mitchell, 1988; Riesco Muñoz et al., 2013). Many of these allometric relationships can be explained by the early work of Shinozaki et al. (1964a), who described the Pipe Model Theory of Tree Form.

2.4.1 The Pipe Model Theory of Tree Form

The Pipe Model Theory of Tree Form (PMT) (Shinozaki et al., 1964a) posits that the non-photosynthetic organs (stems and branches) existing at a certain height (x) above the ground, support both mechanically and functionally, all of the leaves above the x horizon. A unit area of leaves is associated with the downward continuation of non-photosynthetic tissues with a constant cross-sectional area. That is, a unit area of leaves is supported by a 'pipe', the cross-sectional area of which remains constant. The pipe serves to provide both mechanical and vascular function and runs from leaves to stem through all intervening strata.

One of the earliest known observations of this relationship was made by Leonardo Da Vinci in his Notebooks (number 394) where he remarked that, "*All the branches of a tree at every stage of its height when put together are equal in thickness to the trunk (below them)*." (Mandelbrot, 1983).

Shinozaki et al. (1964b) further explored the PMT and found that the root system also adheres to the model; recently summarised by Rodtassana and Poungparn (2012) who remark *"…the total cross sectional area of roots is identical among the different root size classes for an individual plant. The pipe model theory states that the cross-sectional area of the tree stem at ground level supports a fixed total weight of roots*." Earlier work has reported relationships which suggest that stem cross sectional area (CSA) is equal to, or proportional to, the summed CSA of roots at a fixed distance from the trunk centre (Carlson and Harrington, 1987; Kuiper and Coutts, 1992).

Shinozaki (1964b) also recognised the presence of disused pipes, alluding to the partition between functional sapwood and central heartwood. It was posited that, the presence of disused pipes (heartwood) in the basal region and buttress roots accounted for an increased cross-sectional area in these tissues. In this region of butt swell, the cross-sectional area of the conductive tissues no longer conforms to that of the stem above (Coutts, 1987). In this so called zone of rapid taper (ZRT), the primary function of roots is to provide mechanical support and stability (Wilson, 1964; Coutts, 1987). The increased cross-sectional area and distribution of heartwood in these roots has been attributed in part to thigmomorphogenesis, whereby external mechanical stimuli such as wind loading trigger internal mechanisms to yield additional wood (Wilson, 1975; Coutts, 1987; Jaffe and Forbes, 1993; Berthier et al., 2001; Kokutse et al., 2010). Beyond the ZRT, there is little taper between the major branches of woody roots (Wilson, 1964; Deans, 1981) and the total root CSA relates once again to the CSA of the trunk (Kaipiainen and Hari, 1985). Figure 2.1 depicts the PMT temporally from left to right. A young tree is seen with a single unit area of leaves (black ellipse) in the first (left) picture, and with three in the second picture, each supported by a single pipe.

As the tree grows (third picture), it sheds its lowest limbs and the unit areas of leaves (red ellipses) are no longer connected to the pipes inside. The process continues as the tree gains size (fourth picture) eventually forming a full-canopied tree with disused pipes and heartwood (in red) at the centre (fifth picture).

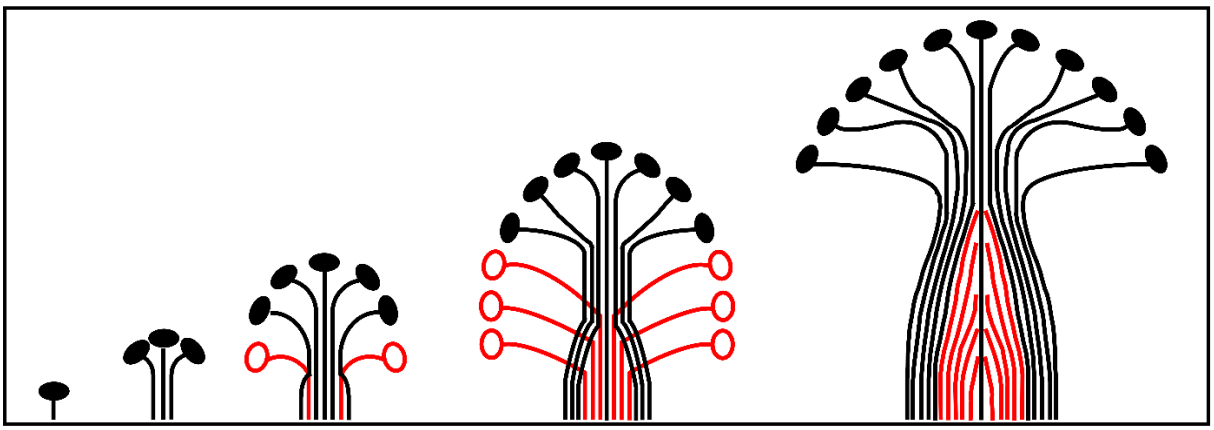

Figure 2.1: Diagrammatic representation of the PMT showing the successive accumulation of disused pipes (red) in the trunk with increasing tree size (Shinozaki et al., 1964a).

It is seen that the PMT explains the relationship between the trunk sapwood area (the used pipes) and other peripheral structures (such as leaves and shoots). Sapwood is the active component in xylem tissue, often found in the outer circumference of a trunk or stem cross-section (Bamber and Fukazawa, 1985; Coder, 2014). This functional region of xylem is responsible for axial water and mineral transport (through xylem lumens) as well as radial movement of defence compounds and carbohydrates (through radial parenchyma) (Shigo, 1986b; Morris et al., 2016). Heartwood (the disused pipes) represents moribund or non-functional xylem (Bamber, 1976; Shigo, 1989b) and plays an important role in passive defence, through the accumulation of secondary compounds such as tannins and polyphenols (Hillis, 1968; Magel et al., 1991; Miranda et al., 2017). The chemical changes involved in heartwood formation often result in a colour change, and the centre of a tree is often much darker than the outer ring of functional xylem (Githiomi and Dougal, 2012). Although the PMT considers the tree as an assemblage of uniformly constructed unit pipes, xylem vessels and tracheids are rarely uniform and are spatially heterogenous, varying greatly with cambial age and relative position in the tree (Gartner, 1995; James et al., 2003; Zhao, 2015). Whilst the PMT remains a useful tool to help understand basic allometry (Lehnebach et al., 2018), it cannot be used to accurately describe or understand how trees are constructed as transport units (Tyree and Ewers, 1991).

2.4.2 Tree allometry and root relations

In the context of arboriculture and urban forestry, the allometric principles of the PMT may be regarded as the foundation on which many of the recommendations relating to trunk diameter-defined offsets (such as tree protection zones) in the various BMPs are based. Knowledge of the extent and distribution of tree root systems is essential for managing trees in the built environment, and is a prerequisite for many arboricultural protocols where site alterations and developments are involved (Coder, 1996; Harris et al., 2004; Standards Australia, 2009; British Standards Institute, 2012). Whilst there have been recent advances in non-invasive root system detection technologies such as ground penetrating radar (GPR) (Dannoura et al., 2008; Zhu et al., 2014), the technology is expensive and not without limitations. For example, objects such as rocks with similar reflection profiles may give false results and accuracies may diminish if there are variations in soil characteristics across the scanning area, or when roots are small in diameter or closely spaced (Butnor et al., 2001; Butnor et al., 2003; Hirano et al., 2009; McBride, 2017). The BMPs rely on an established relationship between trunk diameter and root system architecture to enable the practitioner to easily derive the various tree protection zones, or synonyms thereof.

Besides the many CSA and biomass relationships previously outlined, trunk diameter is an excellent predictor of root (Day et al., 2010) and crown (Peper et al., 2001) spread. Gilman (1989) found strong linear correlations (R^2 = 0.79 – 0.99) between DBH and lateral root spread in five different species of broadleaf trees. Tubbs (1977) found similar correlations (R^2 = 0.80 – 0.85) for two different broadleaf species, as too did Gerhold and Johnson (2003) (R^2 = 0.72 – 0.91) for an additional four. Some local authority texts in New Zealand use the furthest radial branch spread (‘dripline’) or height (Auckland Council, 2018) as a measure of a tree’s root zone, although these are poor predictors of lateral root system spread in urban trees (Day et al., 2010). DBH has been shown to accurately account for 89% of the variability (calculated as R^2) in lateral root spread in urban trees with trunk diameters up to ≈ 70 cm (Day et al., 2010). The same study revealed that the lateral root spread of trees with trunk diameters up to 20 cm could be 38 times that of the trunk diameter; although acknowledged that variation due to species (Gilman, 1989) and soil condition (Gerhold and Johnson, 2003) may be observed.

2.4.3 The root to shoot ratio

Trees, and indeed all plants, contain numerous parts (tissues, organs etc.) which must remain in equilibrated proportions. One such equilibrium is that of the ratio of root material to shoot material, or the root to shoot ratio (R:S) (Wilson, 1988). Whilst attempts have been made to fit the R:S to the allometric growth formula (Equation 2.1) (Pearsall, 1923; Troughton, 1956), the model is entirely empirical, and does not allow for any explaination of growth factors, such as temporal (how the relationship changes over time) or abiotic (such as changes in water or nutrient availability) effects (Wilson, 1988).

$$y = ax^b \qquad \text{(Equation 2.1)}$$

Where y = the dependent variable (in this instance, root dry weight), a and b = constants and x = the independent variable (in this instance, shoot dry weight) (Huxley, 1924). The allometric growth formula is now very commonly used to describe the relationships between tree parts. For example, trunk diameter and leaf area in forest operations (Vertessy et al., 1995).

Recent investigations (Ledo et al., 2018; Mašková and Herben, 2018) into how the R:S is controlled, look to optimal partitioning theory, which suggests that plants will allocate more resources to the organ which is responsible for acquiring the most limiting resource (Reynolds and Thornley, 1982; Johnson and Thornley, 1987). That is; plants will allocate more carbon to roots, if the limiting resources are belowground (e.g. water and nutrients), and to leaves and shoots, if the limiting resources are aboveground (e.g. carbon) (Poorter et al., 2012; Fatichi et al., 2014). This type of allocation plasticity is an important mechanism upon which plants rely, to acclimate to changing environmental conditions (Bloom, 1985; Menges, 1987; Bonifas and Lindquist, 2006).

For trees, the two main factors which control the R:S, are water deficit and size (Ledo et al., 2018). In the case of the latter, where trunk diameter was used as a measure of size, R:S was negatively correlated with increasing size (larger trees have a lower R:S). This is consistent with the fact that older trees are inherently larger than younger trees and that increasing proportions of non-conductive xylem tissues are accumulated over time (Bamber, 1976; Bamber and Fukazawa, 1985; Shigo, 1991) (Figure 2.1). It was found that tree size and water availability are independent of each other; although other evidence points to the contrary (i.e. larger trees are more susceptible to water deficits) (Bennett et al., 2015). As will be seen later, water limiting effects can be achieved through root removal, which in turn can affect the root to shoot ratio (Wilson, 1988).

2.5 A review of root pruning research

Severing roots from trees elicits a range of effects, both positive and negative. Although extensive research into the effects of root loss is lacking (Costello et al., 2017), some work has been done with a narrow range of tree species to investigate the effects of root loss on nursery production, tree stability, growth, and in more recent times using modern analytical equipment, on physiological processes. The following is a review of current information.

2.5.1 Dynamic mass vs static mass: How does tree age affect responses to root loss?

Much of what is known about tree responses to root pruning has been from investigations undertaken on young trees, largely because of the time investment to establish an experimental plot of mature trees. Whilst these results provide valuable information, young trees respond to injury very differently to mature trees, and it is pertinent here to briefly discuss the reasons why.

The symplast is the highly ordered, three-dimensional network of living protoplasm in trees (Shigo, 1986b). Conversely, the apoplast is the network of non-living cells, which in turn are highly ordered and interconnected (Shigo, 1989a). The dynamic mass versus static mass model states that young trees contain living cells (symplast) throughout. They are said to be 100% dynamic mass. As they age, and the energy demands of the living symplast begin to outweigh the available energy, portions of the tree are forced to become altered to static mass (Shigo, 1991). Examples of static mass include protection wood, or heartwood (Bamber, 1976; Bamber and Fukazawa, 1985) (Figure 2.1). The tree must regulate the ratio between dynamic and static mass, to maintain order in the balance of available energy versus energy required. This is somewhat akin to the second law of thermodynamics, which posits that no system will remain orderly, or survive, unless it receives a continuous supply of energy. The dynamic mass fraction of the tree must have a continuous supply of energy if order (survival) is to be maintained (Schreiber and Gimbel, 2010). Whilst the formation of static mass reduces the overall energy demand, it also reduces the tree's ability to respond to injury, largely due to limited nitrogen reserves in the dying or dead wood (Merrill and Cowling, 1966). And, in the case of root removal, a reduced ability to absorb nitrogen and other nutrients from the soil, particularly when water is limiting and root loss is severe (75% total root system removal) (Dong et al., 2016). When optimal partitioning theory is considered, the response to root loss is often to promote new root growth, to compensate for the lost roots and to restore the tree's capacity for water and nutrient uptake (Geisler and Ferree, 1984; Sudmeyer et al., 2004).

At full maturity, the ratio of dynamic to static mass may be as little as 0.05 (5% dynamic mass to 95% static mass). As the ratio between living (symplast, or dynamic mass) and dead (apoplast, or static mass) tissues changes, so too does the tree's ability to respond to injury, and the amount of live tissue lost when functioning tree parts (such as live branches) are removed becomes increasingly significant (Shigo, 1991). Mature trees are therefore much more vulnerable to the effects of removing roots and branches than young trees.

2.5.2 Root pruning and nursery production

The nursery industry is of great importance to the urban forest and commercial tree growers are required to produce high quality stock (Allen et al., 2017). Providing techniques to encourage the growth and survival of newly planted trees is important for the development of the urban forest (Levinsson et al., 2014; Gilman et al., 2016b; Allen et al., 2017).

Research has shown that shaving the root ball (removing the outer 3 to 6 cm of the root ball and growing medium with a sharp spade) of container-grown trees during landscape planting can improve root system architecture, by reducing the numbers of irregular root formations, which may result in girdling injuries and give rise to future tree problems (Gilman and Wiese, 2012). The same study revealed that root ball shaving and root ball slicing (making six vertical slices through root ball equally-oriented around the trunk) improves post-planting anchorage, although others have shown that these effects differ across species and nursery technique (Khuder et al., 2007; Gilman et al., 2016c, 2017). Root ball slicing young container-grown trees in the nursery prior to landscape planting, can positively (Gilman et al., 2016b) or negatively (Gilman et al., 2015) affect above-ground growth.

Manipulating the roots of field-grown trees enables nurseries to maintain their stock at a manageable size under field conditions prior to transplant (Goor and Barney, 1976). When Rook (1971) examined how undercutting (a tractor-mounted horizontal reciprocating saw is used to sever roots of line-sown seedlings at a pre-determined depth) affected the growth of *Pinus radiata* seedlings, root pruning had significant negative effects on height and trunk diameter growth in the short-term (three months) following root severance, but improved post-planting survival by increasing the root to shoot ratio (Shoulders, 1963; Van Dorsser and Rook, 1972). Others have found that post-transplant survival of root pruned field-grown trees is reduced compared to those which have not been root pruned (Mc Nabb and Vanderschaaf, 2005), and that the growth of new roots is affected by the timing at which the root pruning (shaving) is undertaken (Gilman et al., 2016b).

Research into nursery production techniques has generally shown that although there may be reductions in above-ground growth in the short term, the positive effects of improved root system architecture and a high root to shoot ratio can advantageously promote tree longevity.

2.5.3 Root pruning and tree stability

Loss of tree stability is usually related to an alteration in root system architecture (Strong and La Roi, 1983). Typical tree stability studies involve the use of static pull tests, where tension is applied to the tree using a cable and winch. A dynamometer is included in the system and measures the pulling force required to pull the tree to a pre-determined angle (Milne, 1991; Crook et al., 1997; Brudi and Van Wassenaer, 2002; Lundström et al., 2007; Ow et al., 2010). In most instances, the tree is pulled to 1° (or less), since the primary breakage in the uprooting process usually occurs between 2.5° and 4° of bending (Sani et al., 2012).

When investigating strength loss due to root pruning, the methods often attempt to replicate construction activities, where trenching is used to indiscriminately sever roots at a known distance from the tree base, occasionally as a ratio of DBH (i.e. two or three times the DBH). Smiley (2008) investigated the effect of linear root cutting at varying distances to the tree base and found a significant difference in the force required to pull young willow oak (*Quercus phellos*) to a trunk angle of 1° when linear root cutting (trenches) was undertaken closer to the trunk base than three times the trunk diameter at breast height. Smiley concludes that "*....cutting roots closer than three times the trunk diameter should not be recommended."*

In a similar experiment, Smiley later (2014) pulled red maple (*Acer rubrum*) to 1° to investigate the relationships between the pull force required and a), the percentage of roots removed, b), the combined diameter of all roots removed as a proportion of trunk cross-sectional area at 1.37 m and c), the combined cross-sectional area of roots removed as a proportion of trunk cross-sectional area at 1.37 m. He found that increasing root removal intensity negatively affected stability, and correlation coefficients (R^2) of 0.74, 0.54 and 0.82 for these relationships (respectively) were established.

Although the effects of root loss on stability may persist for several years (Fini et al., 2013b), root system morphology and soil type can also influence anchorage and stability (Dupuy et al., 2005b). Ghani et al. (2009) found that mechanical stability was not greatly affected by trenching (root cutting) in *Eugenia grandis*, even when the trench was 0.50 m (≈ 2.3 times trunk diameter) from the trunk; concluding that rooting depth close to the trunk was a major component of tree anchorage.

Research into root loss and tree stability has generally shown that, changes to tree stability only usually become apparent when roots are severed near to the tree base, i.e. the structural root plate, or zone of rapid taper. In the context of the urban environment, where trees share their space with people and structures, understanding how root loss affects tree stability is of great importance. In many jurisdictions, tree managers have a legal duty of care to consider risks (such as whole-tree failure) under their control (Barrell, 2012; Ellison, 2016).

2.5.4 Root pruning and tree growth

Trees maintain a dynamic equilibrium between roots and shoots (Shigo, 1991). If part of the root system dies, so too may a part of the crown die (Perry 1982 Shigo 1991), although there may be a temporal delay (Hamilton, 1988; Hauer et al., 1994; Watson, 1998). Morphological changes such as leaf necrosis, wilting and premature leaf abscission are positive indicators of plant stress (Pallardy, 2008), although may take several years to fully manifest (Watson, 1998; Costello et al., 2017).

Trunk diameter and shoot extension are readily observable features and root pruning studies using landscape trees have demonstrated how these growth variables are affected (Watson, 1998; Fini et al., 2013b). Subsequent recovery from root pruning injuries is dependent on available stored carbohydrate reserves, hormonal signalling, rapid cambial initiation and favourable environmental conditions (Hamilton, 1988).

Watson (1998) examined how root removal affected tree growth and vitality, again adopting linear trenching methods to sever roots at a distance approximately equal to the trunk circumference (≈ 3 times trunk diameter) from the tree base. Mature *Quercus palustris* were exposed to different trenching treatments, being on one, two or three sides, revealing that more severe trenching (more trenches) resulted in greater dieback and reduced tree growth (shoot and DBH growth) and vitality when compared to controls. Other research highlights the variability in the response to root severance among species and reveals that trunk diameter growth is retarded in the short term, immediately after root severance (trenching), but is not significantly reduced in the long term (Pretzsch et al., 2016). Others have observed slightly elevated DBH growth increments when compared to controls following 'minor' root pruning treatments (Watson, 1998; Fini et al., 2013b; Dong et al., 2016). However, there is little argument that DBH growth is reduced in response to more severe root loss.

Root removal negatively affects the root to shoot ratio and plants generally respond by promoting root growth and repressing shoot growth to restore the balance (Geisler and Ferree, 1984; Sudmeyer et al., 2004; DesRochers and Tremblay, 2009). One way this can be measured in young trees, is by looking at height growth.

Height growth may be affected following root severance although with differing results. Mc Nabb and Vanderschaaf (2005) compared root pruned (tap root and lateral roots pruned to 15 cm length) to non-root pruned *Liquidambar styraciflua* seedlings and found no significant differences in height growth in the root pruned samples three years after roots were severed.

Farmer and Pezeshki (2004) compared two different root removal intensities (25% and 75%) in *Quercus nuttallii* seedlings and found that more severe (75%) root pruning resulted in increased height growth compared to less severe (25%) treatments but remained less than controls, 72 days after severance. The reasons for this are not described, although presumably the severely root pruned seedlings required greater carbon resources than the lesser pruned seedlings, to allocate to new root growth, and that it was first necessary to generate more assimilative tissues to satisfy the demand. It was also shown that the root pruning effects on height growth were temporary, alleviating after 108 days, which was attributed to a restoration of the root to shoot ratio in both treatments.

Height growth of hybrid poplar trees (*Populus maximowiczii x balsamifera, P. balsamifera x maximowiczii, P. balsamifera x trichocarpa* and *P. deltoides x balsamifera*) was also reduced compared to controls, two years after root pruning (trees planted as 'whips'. A one-year old dormant seedling which has the roots removed, leaving a bare twig.). The root to shoot ratio of the root pruned trees had not been restored after two growing seasons, accounting for the reduced height growth (DesRochers and Tremblay, 2009).

Dong et al. (2016) pruned *Cunninghamia lanceolata* roots at 25%, 50% and 75% intensities and showed that at 25%, increases in height growth were greater than controls in well-watered plants. Height growth was retarded in more severe treatments, increasing with pruning intensity. The authors explain that, the severity of the response is related to the intensity of the root loss. It was found that by removing 25% of the root system, fine root production and subsequently nitrogen uptake and photosynthesis were increased, which subsequently accounted for the increase in above-ground growth in this lesser treatment.

Investigations involving height growth responses to root pruning are traditionally employed on seedlings or young trees, where height growth can be easily measured by the investigators (Farmer and Pezeshki, 2004; DesRochers and Tremblay, 2009; Dong et al., 2016). For larger trees, height growth measurements can be cumbersome, and there is the possibility of measuring errors.

Traditionally, new shoot elongation is measured (Watson, 1998; Fini et al., 2013b) and can be used as an indicator of how the root to shoot ratio may be affected.

Root removal negatively affects shoot growth in the growing season following the root pruning treatment, although the duration of the effect is variable (Young and Werner, 1982; Ferree, 1989; Autio and Greene, 1994; Khan et al., 1998; Watson, 1998; Fini et al., 2013b; Dong et al., 2016) - presumably depending on how able the trees are to restore the root to shoot ratio, the age of the tree and the extent of root loss. To restore the root to shoot ratio and recover from injury, the plant needs to grow new roots. In doing so, shoot growth is repressed due to the preferential allocation of photoassimilates to the roots (Rook, 1971; Hamilton, 1988). New root biomass may increase with increasing pruning intensity (Farmer and Pezeshki, 2004), although the response varies between species (Hipps et al., 1999) and may be positively influenced when available soil moisture is as low as 35% of field capacity (Dong et al., 2016), when water becomes the limiting resource.

Although it may be common to think that tree growth is a measure of tree health, this is not necessarily the case. Health is the ability to resist stress (any syndrome that interrupts, restricts or accelerates the normal processes of a plant or its parts (Odum, 1985)) and strain (prolonged periods of stress) and is a dynamic condition which combines the intrinsic genetic program (vigour) with the ability to grow under the available conditions (vitality) (Shigo, 1986b). Vigour is the capacity to survive under conditions which threaten survival and can only be measured by applying a known stimulus (e.g. root removal or drought) and measuring the response. Vitality is the ability to grow under the imposed conditions, within the limits defined by vigour and can be improved using cultural practices such as irrigation and fertilisation (Shigo, 1986a). Whilst a ‘snapshot’ of tree health may be defined using visual methods (Blair et al., 2019), LiDAR imagery (Degerickx et al., 2018), determining the presence / extent of internal decay (Helmanto et al., 2018) or thermal imaging techniques (Pitarma et al., 2019), to fully understand tree health, a knowledge of the biological system and the way in which it responds to external stimuli is necessary.

Research into root pruning and tree growth has generally shown that, although the duration of the response varies between species and age, root loss results in curtailment of above-ground growth. Largely this is due to water and nutrient limitation, as well as plasticity in the allocation of available resources to plant parts, whereby shoot growth is repressed in favour of producing new roots.

2.5.5 Root pruning and tree physiology

Understanding and identifying the physiological responses of trees to environmental stress is advantageous to arboricultural and ecophysiological practitioners. Modern analytical equipment can reveal information about tree stress long before the manifestation of visual symptoms (van Kooten and Snel, 1990). Although little attention has been afforded to the physiological responses of urban trees to root pruning, relationships between root severance and a physiological response have been established. Fini et al. (2013b) found small but noticeable reductions in photosynthetic efficiency and CO_2 assimilation over a four-year period when trenching was undertaken 40 cm from the trunk base (≈ 4.5 times DBH) of *Aesculus hippocastanum* and *Tilia x europaea* trees. Root pruning also negatively affected leaf water potential, which decreased with increasing pruning intensity. This study revealed the difference in recovery times among species, alluding to different tolerances to root manipulation among taxa.

Dong et al. (2016) more recently concurred with Fini's results and found additionally that a small amount (25% of total) of root pruning initiated a stress response, resulting in both elevated physiological activity (photosynthesis and gas exchange) and increased biomass. In earlier work, Teskey et al. (1983) observed reduced stomatal conductance and xylem water potential when 43% and 54% of 30 year old *Abeis amabiis* were severed.

The rate of photosynthesis is sometimes increased by root pruning but may take time to become fully apparent (Pallardy, 2008). Photoassimilates have been shown to be translocated to the roots to generate new tissue at the expense of foliage growth in response to undercutting treatments in the nursery (Rook, 1971); and fine root production increases in response to root pruning treatments (Dong et al., 2016).

Investigating fine root biomass in response to root severance is inherently destructive, and these types of studies are often conducted on sacrificial trees at the seedling stage. Farmer and Pezeshki (2004) observed increases in net photosynthesis and stomatal conductance with increasing root pruning intensity (25% and 75% root length removal compared to controls) when *Quercus nuttallii* seedlings were regularly watered. Repeated inundations with water (flooding) however, negatively affected the same physiological responses, which was explained by an anoxic soil environment limiting new root formation. In turn, the decreased root surface area limited the plants' ability to take up water and nutrients from the soil and the trees' physiological processes were hindered as a result.

Research into root pruning and tree physiology has generally shown that, physiological processes can become quickly perturbed as a result of increasing root removal. Many of the physiological responses to root loss can be explained by a chronic but mild water stress in the root-severed trees (Fini et al., 2013b). The inflicted imbalance between water usage by the foliage and resupply from the roots elicits a range of tree responses (Stupendick and Shepherd, 1980; Pallardy, 2008).

2.6 Water stress and the plant response

Water stress is a major limiting factor for tree growth in a range of species (Leuschner et al., 2001; Fini et al., 2009; Martinez et al., 2013a; Weemstra et al., 2013; Marqués et al., 2016). Morphological responses to water stress include reducing canopy leaf area through reduced growth, wilting and later abscission of leaves as a result of reduced turgor pressure, which limits evapotranspiration and water use (Struve and Joly, 1992; Chaves et al., 2003; Liu and Stützel, 2004). Heliotropism is a process where plants can alter the angle of their leaves relative to the sun thereby reducing light interception. Water stress plays an important role in heliotropism which has been shown to maximise water availability and minimise damage to the photosynthetic apparatus during periods of stress (Valladares and Pearcy, 1997; Kao and Tsai, 1998). Reduced water availability limits cell extension (Chaves et al., 2003), shoot growth (Lei et al., 2006; Fini et al., 2009), leaf size (Otieno et al., 2005; Martinez et al., 2013a; Dbara et al., 2016) and annual expansion of woody tissues (Gilman et al., 1989; Lei et al., 2006).

The hydraulic processes of plants are intrinsically tied to carbon allocation and have evolved to maximise carbon gains and water transport during short or long-term fluctuations in environmental conditions (Mackay et al., 2015). Spatial heterogeneity of global climatic conditions has led to the development of a range of plant hydraulic strategies. Under drought conditions, plants exhibiting isohydric behaviour are able to maintain leaf turgor within a narrow range, by limiting transpiration through stomatal closure. However, leaf gas exchange and carbon assimilation are negatively affected (Tyree and Sperry, 1988; Choat et al., 2012; Manzoni et al., 2013). Conversely, the stomatal apertures of anisohydric plants remain open, even when leaf turgor drops (Tyree and Sperry, 1988; McDowell et al., 2008; Sade et al., 2012; Martínez-Vilalta et al., 2014), allowing for carbon assimilation to continue. Anisohydric behaviours may be somewhat of a risk for the plant should the period of drought not be restored to more favourable conditions (e.g. when water becomes more available). However; this type of response has been shown to improve resistance to cavitation (Linton et al., 1998; Brodribb and Holbrook, 2004; Alsina et al., 2007) and long-term drought survival (Bonal and Guehl, 2001; Loewenstein and Pallardy, 2002; Breshears et al., 2005; Shaw et al., 2005), making the risk of desiccation worthwhile.

Physiological responses to water stress are regulated by chemical signalling, which may act directly upon (Liu et al., 2001a), or at distance from the affected tissue (Hetherington and Quatrano, 1991; Liu et al., 2001b). Many plants show an ability to recover from water stress when water availability returns (Sun et al., 1995; Romero et al., 2004; Souza et al., 2004; Percival et al., 2006; Galmés et al., 2007; Naumann et al., 2010; Mellisho et al., 2012; Fini et al., 2013a), but during extreme periods of drought, a complete hydraulic disconnection of roots to shoots (cavitation) may arise, and complete recovery may not be possible (Loewenstein and Pallardy, 2002).

2.6.1 Water stress and leaf water status; leaf turgor and water potential

Pre-dawn leaf water potential is a highly sensitive measure of plant water status. In the early hours of the morning prior to sunrise, the leaf water status of a plant is assumed to be in hydraulic equilibrium with the soil. Measurements taken before dawn - usually between 03:00 a.m. and 05:00 a.m. - allow for an examination of leaf turgor in the absence of influence from meteorological conditions such as heat and light, and provide a valuable insight into the plant's water availability (Améglio et al., 1999). Pre-dawn leaf water potentials of treatment trees have been shown to decrease significantly from controls during water stress (Epron et al., 1992; Kubiske et al., 1996; Zwack et al., 1998; Fini et al., 2013a) and root pruning (Fini et al., 2013b; Wang et al., 2014; Dong et al., 2016) studies, when soil water availability becomes limiting.

2.6.2 Water stress and leaf gas exchange

Closing stomatal openings limits water loss through transpiration and protects other plant tissues from dehydration, by maintaining turgor and limiting cavitation (Chaves et al., 2003). Stomatal closure is more affected by available soil water levels than leaf dehydration (Chaves et al., 2002; Rouhi et al., 2007), and is likely to be mediated by chemical signals travelling from dehydrated roots (Schulze, 1986; Liu et al., 2001b). Abscisic acid is closely involved in the signalling pathway and stomatal conductance (water loss through stomatal apertures) has been shown to decrease in response to increased concentrations of abscisic acid in the xylem sap (Loewenstein and Pallardy, 2002) and leaves (Zaharah and Razi, 2009). Stomatal conductance measurements made using modern leaf porometers are quick and easy to use (Montague et al., 2008). The rate of photosynthesis (net carbon assimilation) is closely correlated with stomatal conductance, highlighting the interconnectivity of these two processes (Cowan et al., 1979; Epron and Dreyer, 1993; Parvizi et al., 2016). Net carbon assimilation is often curtailed during periods of water stress when stomatal apertures are closed (Fernandez et al., 1997; Arend et al., 2013; Fini et al., 2013a; Dong et al., 2016)

2.6.3 Water stress and photosynthetic performance

Stomatal closure in response to drought can result in potentially injurious conditions for the photosynthetic apparatus, if the available carbon sink (CO_2) needed for photochemical processes (the light independent reaction) becomes depleted (Flexas et al., 1999). This can expose the photosynthetic reaction centres and associated proteins to excess excitation energy resulting in damage to the photosynthetic apparatus (Powles, 1984; Long et al., 1994; Ort, 2001; Keren and Krieger-Liszkay, 2011).

The advent of modulated measuring devices has made investigations into the photosynthetic mechanism quick and easy (Quick and Horton, 1984; Krause, 1991). The photosynthetic performance of plants can be measured using chlorophyll fluorescence spectrometry (Maxwell and Johnson, 2000). The principle of chlorophyll fluorescence relies on the premise that the fate of the light energy absorbed by chlorophyll molecules in a leaf can take one of three routes. It can be used to drive photosynthesis (photochemistry), or be re-emitted as light (fluorescence), or heat (non-photochemical quenching). By measuring the re-emitted light in dark-adapted leaves, it is possible to gain an understanding about the maximum photochemical efficiency of the photosynthetic (PSII) apparatus in the absence of non-photochemical quenching.

The most common fluorescence parameter used to reveal information about the performance of the PSII apparatus is Fv/Fm. Typical values of Fv/Fm in unstressed leaves of most plants are ≈ 0.75 - 0.83 (Krause, 1991; Maxwell and Johnson, 2000). Changes in the value of Fv/Fm may be due to photo-inhibition, which can happen when proteins (particularly the D1 protein) in the PSII apparatus are damaged through photo-oxidation during stomatal closure (Powles, 1984; Long et al., 1994; Ort, 2001; Keren and Krieger-Liszkay, 2011)

2.7 Summary of literature

Trees in the urban environment, individually and collectively provide numerous benefits to society (Brouwer et al., 2013; Morgenroth et al., 2016), making them valuable components of the modern urban environment (Dwyer et al., 1992). Establishing trees in urban settings is challenging, and there are constraints to growth and survival (Konijnendijk et al., 2006; Bartens et al., 2010). Such challenges may take the form of sub-optimal growing environments, where root volumes are insufficient to support growth (Grabosky et al., 2002; Layman et al., 2016) or soils are poorly structured and compacted resulting in poor water infiltration (Miller and Miller, 1991; Whitlow et al., 1992; Pauleit et al., 2002). Once established, modern engineering requirements and urban development can negatively affect tree survival (Hauer et al., 1994; Koeser et al., 2013; Guo et al., 2018; Guo et al., 2019). Root losses during pavement repairs (North et al., 2017) or utility installation (Jim, 2003) are common and contribute towards these outcomes.

Roots are important tree structures, and play vital roles in tree stability (Danjon et al., 2005; Peltola, 2006), water uptake (Tyree, 2003) and carbon storage (Coutts, 1987; Hartmann and Trumbore, 2016). Removing roots from container (Gilman and Wiese, 2012) or field-grown (Rook, 1971) nursery trees can improve root system architecture, increase root to shoot ratios and post-transplant success. However, removing roots from mature trees can negatively affect growth and vitality (Watson, 1998) and increase the likelihood of windthrow (Smiley, 2008; Smiley et al., 2014). Modern analytical equipment has been used to detect early physiological stress symptoms in trees exposed to root removal, revealing that root removal produces symptoms of water stress in the affected trees (Fini et al., 2013b).

The negative effects of root pruning on tree health and stability, concomitantly affects the health and population of the wider urban forest, thus reducing the benefits of trees to the wider community. To protect trees from damage and limit the negative effects of urban development and construction, a range of best practice documents exist. However; the pool of knowledge in this field is limited, and further research is required to provide greater information to the industry, in order that current practices may be further improved.

2.8 Aims and objectives of this research

The main aims of this thesis are:

1) To test the suitability of trunk diameter-derived offsets for tree root protection guidelines. Specifically;
    a. Tree protection zone radii, and
    b. Trenching distances

2) To investigate whether root removal affects growth, physiology and tree value in the short term.

3) To test the suitability of allometric relationships between root and trunk cross-sectional areas as a tool to quantify root pruning doses.

4) To take the first steps towards developing a practical tool for arboricultural practitioners who make day-to-day decisions relating to roots and root care practices.

To do so, experiments have been designed to answer the following research questions:

Research question 1: What effect will an increasing number of trenches in which roots are severed have on tree growth and physiology?

Research question 2: How big does a tree protection zone need to be to avoid the negative effects on tree growth and physiology?

Research question 3: How close to a tree can roots be severed in a linear trench before sustained stress symptoms are observed?

Research question 4: How does root pruning affect tree monetary value when trees are valued using common valuation methods?

Research question 5: Can the allometric relationship between trunk and root cross-sectional area be used as a tool to quantify a root pruning threshold above which negative effects are avoided?

2.9 Null hypotheses

Increasing root removal will have no effect on the following tree growth responses:

1) Trunk diameter growth
2) New shoot extension
3) Leaf area
4) Tree condition

Increasing root removal will have no effect on the following physiological responses:

1) Pre-dawn leaf water potential
2) Stomatal conductance
3) Chlorophyll fluorescence variables

Increasing root removal treatments will have no effect on tree value.

Chapter 3: Experimental design

3.1 Study sites and trees

To test the null hypotheses that root pruning has no effect on tree growth, physiology and monetary value, three experiments were designed and undertaken in four locations. This chapter describes the basic details of each of the experimental sites, as well as the methods which are common throughout this thesis. Full detailed descriptions of the methodological approaches and the statistical analyses are included in the relevant section of each of the results chapters (Chapters 5 to 8).

At the commencement of the research, the biggest constraint was that of procuring or sourcing trees. The requirements were that there needed to be a sufficient number of trees in an early-mature to mature age class to experiment upon within a secure location. Although procurement of suitable trees was a major challenge at the outset of the project, options became available. The type of research which has been undertaken in this thesis is unique within the New Zealand, and as such, establishing trees for research purposes is uncommon outside of forestry (i.e. timber crops). Nevertheless, a quantity of trees became available for use in the investigation, albeit with caveats (described later in 3.4). To augment the work undertaken in New Zealand, overseas options were also explored. Through academic relationships and funding, it was possible to visit the USA for six months, where arboricultural research and resources are more abundant, and numerous mature trees were available to be worked upon. The trees made available in the USA supplemented those which were available in New Zealand such that a total of three experiments were undertaken, exposing trees to different types of root removal.

The first experiment was undertaken across two sites in New Zealand's Waikato region. Two further experiments were undertaken at two locations in Florida, USA. Experiments commenced at the two New Zealand sites in November 2016, at the start of the 2016 / 2017 summer growing season. The experiments in Florida commenced in May 2017 for the 2017 summer growing period in the northern hemisphere

3.1.1 New Zealand study sites

Study sites in New Zealand were selected based on the availability of trees suitable for root manipulation. Tāmata Maples (Site 1, 37° 48’ 37.85” S. 175° 24’ 56.61” E) is a commercial tree nursery specialising in field-grown *Acer* varieties, the proprietor of which generously donated trees for experimental purposes. Totara Park (Site 2, 37° 44’ 43.31” S. 175° 15’ 0.01” E) is a publicly managed passive recreation reserve, owned and operated by Hamilton City Council. Trees at Site 2 had been planted and allowed to establish as future stock for the city’s street tree asset. The intention was for them to be transplanted to a permanent location at a later stage. Due to changing objectives and personnel within the council’s organisational structure, this was no longer the case and the trees were generously made available for inclusion in the study. The location of both study sites relative to Hamilton City are shown in Figure 3.1.

At Site 1, one hundred *Acer palmatum* ‘Bloodgood’. Thunb grafted onto *A. palmatum* rootstock were randomly selected from a single block of 201 trees spaced 4 m between rows and 2 m along rows. A group of 19 *Acer negundo*. L growing in a linear arrangement spaced approximately 4 m apart were used in the study at Site 2.

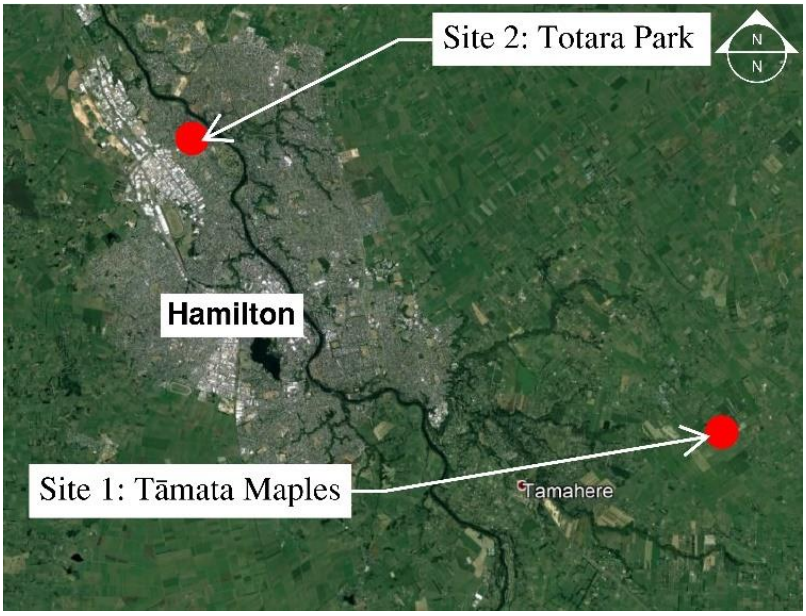

Figure 3.1: New Zealand study site locations

3.1.2 Florida study sites

Study sites in Florida consisted of two University of Florida research facilities, those being the Plant Science Research and Education Unit (PSREU, 29° 24’ 37.19” N. 82° 09’ 57.96” W) and the Gulf Coast Research and Education Center (GCREC, 27° 45’ 41.76” N. 82° 13’ 41.01” W). At PSREU, 18 open - grown *Quercus virginiana* Mill ‘SDLN’ grown for experimental purposes in a grassed area were used in the study. At GCREC, 31 *Quercus virginiana* Mill were suitable for the study. The trees at GCREC had not been grown experimentally, they were in fact landscape trees growing in a lawn area surrounding the research facility, although their root zones had not been manipulated since planting. A low-volume asphalt road surface ran parallel to the grass that forms the trees’ growing environment. The location of PSREU and GCREC are shown in Figure 3.2.

Figure 3.2: Florida study site locations

3.2 Root pruning treatments

To test the individual hypotheses, at each study site, the selected trees were exposed to different root pruning treatments (the two New Zealand study sites had identical treatments). In order to investigate the allometric hypothesis, it was necessary to discriminately sever and collect individual root fragments from each of the trees. To do so, trenches (≈ 100 mm wide, ≈ 500 mm deep) at each site were undertaken using pneumatic soil displacement (Air Spade, Guardair, Chicopee, MA, USA), and all exposed roots were individually removed using sharp cutting tools (such as loppers or a handsaw) and bagged for subsequent measurement. Whilst there may have been a small number of deeper roots below 500 mm not exposed with the Air Spade, the trenches at all study sites were devoid of observable root activity at the 500 mm mark.

Trees at each of the New Zealand study sites were randomly exposed to one of four treatment types plus a control. Those being; a trench on one side of the tree (T1), parallel trenches on two sides of the tree (T2), trenches on three sides of the tree (T3), or trenches on four sides of the tree (T4) (Plate 3.1). Trenches were made at a fixed distance of 30 cm from the tree base at the start of December 2016. The purpose of this study was to gather a wide range of root sizes and numbers to test the allometric hypothesis and to answer research questions 1 and 5.

Plate 3.1: Depiction of root pruning treatments at Tāmata Maples. Left to right: T1, T2, T3, T4

At PSREU, trees were randomly allocated to one of five treatment groups plus a control. Because many of the trees had branching at 1.40 m, treatments were prescribed based on trunk diameter at 1 m. Treatments consisted of a circular trench around the base of each tree with a radius defined by its trunk diameter. Treatments ranged from 3 to 15 times the trunk diameter (3x to 15x) in increments of 3 (Plate 3.2) and were undertaken at the end of June, 2017. The purpose of this study was to test a range of tree protection zone sizes, and to answer research questions 2 and 5.

Plate 3.2: Depiction of root pruning treatments at PSREU. Top, left to right: 15x, 12x, 9x. Bottom, left to right: 6x and 3x treatments

At GCREC, trees were randomly allocated to one of three treatment groups plus a control. Treatments made in early June, 2017, consisted of a single linear trench, offset from the tree base at a distance equivalent to 3 (3x), 6 (6x) or 12 (12x) times the trunk diameter at 1.4 m (Plate 3.3). The purpose of this study was to simulate root severance by utility trenching and to answer research questions 3 and 5.

To answer research question 4 (does root pruning affect monetary value?), prior to root manipulations the trees at each site were appraised and valued using four, common parametric tree appraisal methods. The trees were appraised and valued again at the end of the first growing season following root loss, and the two values (before and after) compared to produce a percentage change in value.

Plate 3.3: Depiction of root pruning treatments at GCREC. Left to right: 12x, 6x and 3x treatments

After first removing all loose soil material, the diameters of all root fragments at the point of severance closest to the tree in two perpendicular planes (d_1 and d_2) for each treatment tree at each site were measured using a digital Vernier calliper (accurate to 0.01 mm). Diameters measuring 2 mm or more (Lyford, 1980) were recorded and root cross-sectional areas (*RCSA*) for each root were estimated using Equation 3.1.

$$RCSA = \frac{\pi(d_1 \times d_2)}{4} \quad \text{(Equation 3.1)}$$

Trunk cross sectional areas at height *x* ($TCSA_{(x)}$) were calculated from circumferential measurements (*C*) of the trunk prior to root manipulation using Equation 3.2. The Area Ratio between combined root cross-sectional area ($\sum RCSA$) and trunk cross-sectional area at height *x* was determined for each tree using Equation 3.3 and is henceforth referred to as $Ar_{(x)}$.

$$TCSA_{(x)} = \frac{C^2}{4\pi} \quad \text{(Equation 3.2)}$$

$$Ar_{(x)} = \frac{\sum RCSA}{TCSA_{(x)}} \quad \text{(Equation 3.3)}$$

Since the allometric principals of the root cross-sectional area ratio relate to the Pipe Model Theory of Tree Form (Shinozaki et al., 1964a, b), and thus the relationship between trunk conductive sapwood area and peripheral tissues, the trunk sapwood area of the study trees was estimated. Root cross-sectional areas were then expressed as proportions of the trunk conductive sapwood area at height *x* ($TCSWA_{(x)}$) using Equation 3.4 and are henceforth referred to as $As_{(x)}$. Sapwood areas were estimated either by microscopic evaluation of harvested timber fragments or wood cores (De Micco et al., 2016) at the two New Zealand study sites, or through the use of electrical resistance tomography (Benson et al., 2018) at the two Floridian sites.

$$As_{(x)} = \frac{\sum RCSA}{TCSWA_{(x)}} \qquad \text{(Equation 3.4)}$$

3.3 Tree responses to root pruning

At each experimental site, the responses of the trees to the root pruning treatments were measured by gathering data on physiological and morphological behaviours. This description serves as a broad overview of the response data. Detailed descriptions of the data collected, and the frequencies of collection can be found in the respective results chapters for each investigation.

In New Zealand, the physiological response data consisted of stomatal conductance and dark-adapted chlorophyll fluorescence responses, to examine how leaf gas exchange (transpiration through stomatal apertures) and the photosynthetic process were affected by root loss. Given the number of trees used in the study, and the frequency with which the physiology data were captured, the inclusion of pre-dawn leaf water potential was dismissed, favouring instead to collect and combine morning and afternoon physiology data. In Florida, pre-dawn leaf water potential was included in favour of afternoon conductance and fluorescence readings. Data gathering exercises were carried out approximately fortnightly, when weather conditions were favourable. Trunk diameter growth, new shoot extension and leaf area served as morphological growth response variables for each of the trees, as well as the percentage change in value.

3.4 Experimental limitations

3.4.1 Logistical constraints

Each experiment was constrained by various factors. In New Zealand, at Tāmata Maples, the nursery proprietor had elected to remove all of the trees in favour of growing alternative crops. Thus, the limitation of the New Zealand study was time and the caveat placed upon the donation of trees was that all work must be completed no later than the end of June 2017. This meant that it was only possible to carry out this experiment during a single growing season.

The two Floridian experiments were also constrained by time, although for different reasons. Immigration restrictions only permitted a six-month stay in the USA during 2017. Budgetary constraints also precluded a longer duration and also the provision of third-party assistance to gather data beyond the accounted for six-month stay in Florida. The planned duration of each of these studies was 1st May to 15th October 2017, inclusive of tree selection and experimental design.

In August of 2018, the author attended the International Society of Arboriculture's conference in Columbus, Ohio (USA), making it possible to briefly visit GCREC and spend an additional week gathering data. It was not possible to visit PSREU due to logistical constraints.

In the final weeks of the Floridian experiments, the regions in which the studies were undertaken were exposed to Hurricane Irma (Cangialosi, 2018). Aside from the obvious meteorological conditions, the effects of Irma on the region included power outages and road closures. Consequently, it was not possible to access PSREU for some weeks to gather data.

3.4.2 Porometer calibration and DLC-8 leaf clips

At the start of the New Zealand experiment, 51 DLC-8 light exclusion clips (for use with a Walz Mini-PAM fluorescence spectrometer) and an SC-1 calibration kit (for use with a Meter SC-1 leaf porometer) were ordered from the supplier in Australia. Despite assurances that the items would arrive prior to Christmas, the items were not received until January 14th, 2017. Fluorescence data gathering began at this time.

Unfortunately, the hydrophilic filter paper discs usually contained within the SC-1 calibration kit were mistakenly replaced with hydrophobic Teflon paper discs prior to dispatch from the supplier. Since the calibration procedure relies upon a wetted disc of filter paper, the subsequent calibration done on January 14th was incorrect. The manufacturer and distributor were immediately contacted, and a correct set of filter paper discs were mailed. Delivery took almost two weeks and a successful calibration was performed on the 31st January 2017, after which conductance measurements proceeded with confidence. All data gathered prior to the correct calibration were discarded, since the previous calibration date and quality were unknown.

The SC-1 device was calibrated again in Florida under local conditions, prior to conductance data being gathered in either of the two Floridan experiments. The fluorescence spectrometer used in the New Zealand study (Walz Mini PAM) was not available during the May to October period of 2017, and thus an alternative device (Optisciences OS30P+) was used.

Chapter 4: Estimating sapwood area using tomography

The contents of this chapter have been reproduced from:
Benson, A., Koeser, A. and Morgenroth, J. (2018). Estimating conductive sapwood area in diffuse and ring-porous trees with electronic resistance tomography. Tree Physiology 39 (3), 484-494. 10.1093/treephys/tpy092

4.1 Preamble

Whilst investigating the allometric hypothesis, which has been founded on the principles of the Pipe Model, it was necessary to estimate the conductive sapwood area of the investigated trees. In New Zealand, this was done destructively, by taking wood samples (either cores or by harvesting trees). The trunk wood of the trial species used in Florida (*Quercus virginiana*) is particularly robust, and during increment core extractions to evaluate sapwood radii, the steel increment core snapped on one of the earliest trees to be sampled. The method was abandoned in favour of a more efficient and less damaging approach.

This chapter describes a method which was developed using electrical resistance tomography to estimate sapwood area. It was necessary to validate the results of the tomographic data and this was done using a dye-perfusion test on a sacrificial subset of *Q. virginiana*. The method is included here as part of the methodological component of the thesis for context and is later referenced in Chapters 6 and 7.

4.2 Introduction

Examinations of tree-stem cross-sections often reveal a central region of darkened heartwood, surrounded by a ring of lighter coloured, conductive sapwood (Bamber and Fukazawa, 1985; Githiomi and Dougal, 2012; Lin et al., 2012). Estimating sapwood area is critical for ecohydrological studies such as transpiration and water balance experiments (Clearwater et al., 1999) and is also of interest to forest managers who have a commercial interest in sapwood volumes (Pereira et al., 2003). Thermal dissipation probes are a common method for estimating tree or stand transpiration (Granier, 1987; Wullschleger et al., 2001) and thus are a critical tool for understanding the hydrological dynamics of forests (Ford et al., 2007). However, the point-flow sap-flux observations obtained from thermal dissipation probes need to be up-scaled across the entire sapwood area (Zhang et al., 2015) and incorrect estimates of sapwood area are a major source of error in this process (Clearwater et al., 1999). Beyond forest hydrology, understanding the sapwood area of timber crop trees is advantageous since the sapwood is merchantable in the paper industry (Pereira et al., 2003). Allometric models for forest crops are often established using trunk diameter to explain sapwood area (Vertessy et al., 1995; Gould and Harrington, 2008; Lubczynski et al., 2017b).

Traditional methods to quantify sapwood can be invasive and injurious to the tree. The most common method involves extracting narrow diameter (≈ 5 mm) wood cores at one or more circumferential positions at the location of inquiry. For trees with distinct colour differences between heartwood and sapwood – the heartwood is usually much darker than the sapwood, owing to the deposition of polyphenolic compounds (Jorgensen, 1962) - the location of the sapwood-heartwood (SW/HW) boundary can be determined either by a visual inspection of the interface between different coloured wood, or examined using chemical staining, whereby different chemical compounds will stain heartwood and sapwood different colours, based on their chemical compositions (Bamber and Fukazawa, 1985). Often a mean sapwood width is derived by extracting multiple core samples, usually in each of the four cardinal directions. The sapwood area is then calculated by assuming cross-sectional uniformity at the measuring height and rotating the sapwood thickness 360° around the cross-section.

More invasive methods involve individual tree felling to examine cross sections and either determine the SW/HW interface based on colour differences or chemical staining as previously described. Felling trees for sapwood area assessment precludes subsequent sap-flow studies, however there are advantages when tree felling is applied to forest resource applications, whereby allometric equations for sapwood area for forest stands can be developed from a subset of the population (Vertessy et al., 1995; Gould and Harrington, 2008; Lubczynski et al., 2017b).

Microscopy, or light table techniques examine the wood for tylosed vessels (Githiomi and Dougal, 2012). Dye-perfusions draw coloured dye through short sections of wood under vacuum. Conductive sapwood regions are stained by the dye and non-conductive regions remain unstained (Hoffman, 2012), although this method is again destructive.

In scenarios where coring or felling trees is undesirable or impractical, a less invasive method based on electric resistance tomography (ERT) has been used to locate the SW/HW interface (Bieker and Rust, 2010b; Lin et al., 2012; Guyot et al., 2013; Wang et al., 2016). ERT is an inspection method originally developed in the field of geophysics. It was originally designed to locate underground water or contaminants by recognising anomalies in the electrical resistance of soil (Daily, 1995). In trees, tomographic techniques have traditionally been used as a minimally-invasive method of assessing wood quality and identifying areas of internal decay, enabling arboricultural practitioners to make informed tree management decisions (Rust and Göcke, 2008; Bieker et al., 2010; Martin and Gunther, 2013).

ERT technology was first applied to trees in 1998 (Just and Jacobs, 1998) using adapted geophysical instrumentation and modified inversion algorithms. A recent focus on the technology and its application has facilitated the development of commercially available devices employed for tree decay detection (Rust and Göcke, 2008). The measurements are undertaken using point-like electrodes (nails or needles) driven into the tree circumferentially with even spacing. An electrical current is transmitted through each electrode pair and measured in pairs by other electrodes until all combinations of transmit and receive are complete.

Conductive tissues in the tree contain an aqueous solution of ions and facilitate the flow of electricity by ion movement (Fensom, 1966). The electrical resistivity of living wood is therefore affected by wood moisture content, secondary compounds and ionic concentrations (Shigo and Shigo, 1974; Kubo and Ataka, 1998; Meerts, 2002; Bieker and Rust, 2010b, a). Differences in conductivity are shown on a relative scale for each ERT cross section with different colours representing different resistivity values. When the sapwood contains a higher moisture content and greater concentration of free ions than the heartwood, then the sapwood area is depicted on the ERT tomogram using a colour representing low electrical resistance (blue in the following figures). Ion rich heartwood in some species can increase conductivity, and the colours on the relative scale are reversed (Bieker and Rust, 2010a). The technique has been used in recent times with proven success to locate the SW/HW interface (Bieker and Rust, 2010b; Lin et al., 2012; Guyot et al., 2013; Wang et al., 2016), and has also been shown to be effective in detecting sap-flow (Hagrey, 2007).

The purpose of this study was to further test the validity of electrical resistance tomography and to compare its effectiveness at estimating sapwood widths for common diffuse and ring porous species in southern North America. To do so, the results of tomographic analyses were compared with those of dye perfusion testing. As far as is known, ERT technology has not previously been used to estimate sapwood area on the species which have been analysed in this study. Additionally, the methods developed for the analyses are provided as an open source tool to use for estimating sapwood area using ERT.

4.3 Materials and methods

4.3.1 Site description and trees

Trees were selected and harvested from two different sites in Florida (USA). The first site was the University of Florida's Gulf Coast Research and Education Center (27° 45' 40.84" N. 82° 13' 40.28" E) situated approximately 30 km south east of the city of Tampa, Florida, USA. The second site was the University of Florida's Tree Unit in Gainesville, Florida, USA (29°37'29.42" N. 82° 21' 17.14" E).

Three different species were selected for the experiment – two ring porous (*Quercus nigra* L. and *Q.virginiana* Mill.) and one diffuse porous (*Acer rubrum* L.). As far as is known, no other study has compared the effectiveness of ERT at locating the SW/HW interface of these wood types or species. Five different *Q. nigra* trees were analysed and harvested from the first site. Seven *Q. virginiana* trees and five *A. rubrum* trees were analysed and harvested from the second site. Each tree yielded multiple samples at different heights on the trunk or on a primary scaffold branch to encompass a range of trunk and branch diameters. Seven samples were analysed for *Q. nigra*, 19 for *Q. virginiana*, and eight for *A. rubrum*. Table 4.1 details the various dimensions of the measured trees.

For the majority of samples analysed from *Q. virginiana*, and *A. rubrum*, electrical resistance tomography was carried out on each sampled tree in-situ at two to four different heights on the trunk or on a primary scaffold branch. Analyses conducted on samples above 1.5 m, which could not be readily accessed from the ground with the instrument, were analysed immediately after the trees were felled. Complete access to the *Q. nigra* trees was constrained by a steep embankment adjacent to a stream known to support alligators, making in-situ ERT analysis impractical. These trees were harvested individually and immediately taken to the on-site laboratory to undertake the ERT analyses (<30 minutes between harvesting and completion of ERT) and subsequent dye perfusion testing. Trunk and branch samples from trees at the second site were transferred on ice to the first site and cold stored at 14 degrees Celsius in a dark room until dye-perfusion testing could be carried out (72-92 hours after felling).

4.3.2 Electrical resistance analysis

A multichannel, multi-electrode electrical resistance tomograph (PiCUS TreeTronic, Argus Electronic GmbH, Rostock, Germany) was used to perform the ERT analyses. A minimum length of clear trunk (free of branch unions) equivalent to twice the diameter of each measured section at each measuring height for each tree of each species remained above and below each ERT cross section.

Using a hammer, electrically conductive nails were driven into each tree at each measuring height with an even circumferential spacing. The minimum number of nails used was eight, and the maximum number was ten. When using ERT in trees, the nails must be in contact with moist wood. Nails were driven just far enough into the trunk sections to penetrate the bark tissue and contact the functioning xylem beneath. A distinct audible change to the struck nails was detectable when the xylem was contacted. On smaller stem sections where the bark was thinner, the nails were replaced by electrically conductive pins inserted by hand, with a noticeable resistance to insertion once the bark had been penetrated. The positions of all nails were marked on the sample and the geometry of the tree's cross section was then established using the accompanying wireless calliper unit (PiCUS Calliper, Argus Electronic GmbH, Rostock, Germany).

Whilst other methods have suggested removing the bark prior to inserting the electrodes (Guyot et al., 2013; Wang et al., 2016), the bark in this study was left in-tact, to better replicate a minimally-destructive means of sapwood area estimation. Furthermore, bark removal was not suggested by the manufacturer of the ERT device employed in this study.

Crocodile clip style electrodes were then attached to each of the nails / pins and an electrical current was passed through pairs of electrodes by the ERT. The current and voltage were determined by another pair of electrodes until all combinations of transmitting and receiving current / voltage had been carried out (approximately 30 seconds). The accompanying software (Q73 Expert, PiCUS, Argus Electronic GmbH, Germany) then deciphered the electrical resistance data and produced a coloured tomogram (Figure 4.1). The image consists of a grid (or mesh) of tessellating triangles, with each triangle having its own electrical resistance reading. For all ERT analyses, mesh fineness was set to 8 and smoothness to 20, which respectively set the number of triangles in the tomogram image (increased mesh fineness yields more triangles) and the level of detail between features or areas of differing resistivity (low smoothness (<10) will display individual features more than larger values (>100) but may suffer more from measuring errors).

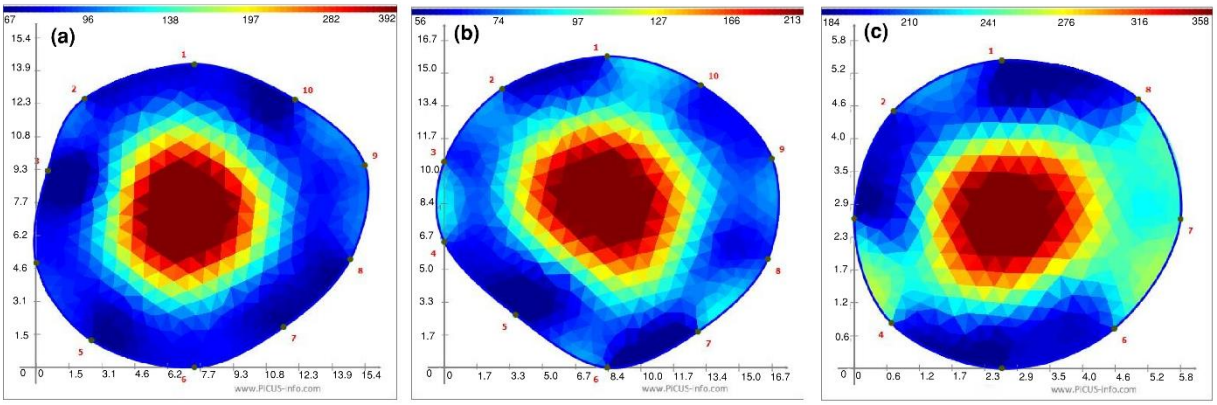

Figure 4.1: Examples of ERT images for (a), *Quercus virginiana*, (b), *Quercus nigra* and (c), *Acer rubrum*. X and Y axes denote distance in cm and electrical resistivity (Ω) is shown on a scale ranging from blue (low resistance) to red (high resistance) at the top.

4.3.3 Dye perfusion test

Following the ERT analysis a ≈ 20 cm section of the trunk / stem at the ERT location was excised using a sharp handsaw. The downstream (top) end of the section was then placed inside a funnel. Using a commercially available expanding sealant foam and taking care not to contact any of the exposed sapwood, a seal was established between the funnel and the wood, which was then left to dry for approximately 30 minutes. Once dry, the upstream (bottom) end of the wood section was immersed in a dye solution (consisting of a 1:1 dilution of food-safe dye and water) in a shallow (2-3 mm deep) bath. Negative pressure (≈ 0.3 - 0.7 MPa) was established by attaching the funnel to a vacuum pump via a short length of hose and the dye solution was drawn through the wood section (Figure 4.2).

Immediately after the dye had been drawn, the wood section was removed from the funnel and dissected through the cross section at the location of the ERT analysis using a sharp handsaw. The exposed face was then scraped with a razor blade to remove any residual dye carried through by the dissection process, and the conductive sapwood boundary was identified based on the interface of stained and non-stained wood. For ring porous species, this was usually located on the boundary of an early-wood ring which had not received any of the dye. For diffuse wood, the dye interface was distinct, however earlywood rings were less visible.

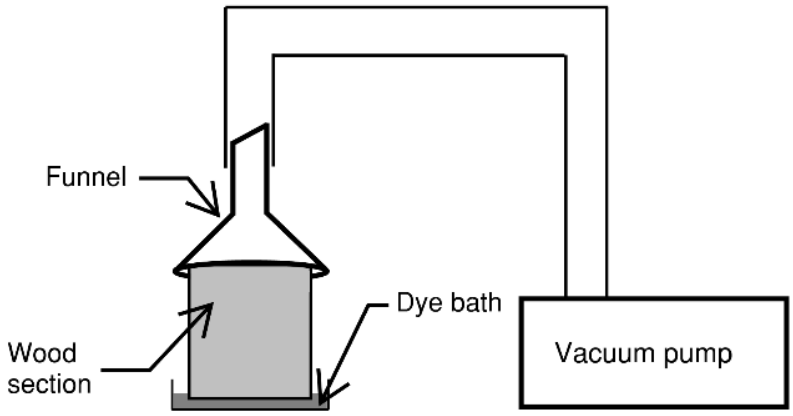

Figure 4.2: Diagrammatic representation of vacuum pump assembly and dye bath

4.3.4 Comparing ERT and measured sapwood boundaries

To determine the position of the SW/HW interface using the ERT, the method described by Wang et al. (2016) was adapted. The extracted resistivity information is in tabulated form containing seven columns of data. The first three pairs of columns are spatial coordinates (x, y) for the corners of each triangle based on the measured tree geometry. The seventh column is the resistance data in ohms for the corresponding triangle. Resistivity data were extracted in eight equally oriented (22.5°) bandwidths (1 – 4 cm) through the geometric centre of the tree section. Bandwidth data were analysed using R Statistical Software version 3.4.4 (R Core Team, 2018). Polynomial regressions were fitted to the data points in each bandwidth using a six and seven order fit. The fitted regression curve with the highest R^2 value was then used to determine the SW/HW interface in each bandwidth by locating the two steepest parts of the curve, as described by Wang et al. (2016).

Bieker and Rust (2010b) recorded the presence of a transition zone between sapwood and heartwood on rendered electrical resistance tomograms, corresponding to a steep rise in resistivity in this zone. The extractive content in sapwood gradually increases from the outer sapwood edge towards the heartwood, with a sharp increase at the SW/HW interface (Hillis, 1968). The boundary between sapwood and heartwood is characterised by a zone of heightened enzyme activity and extractive deposits (Nair, 1988; Magel et al., 1991; Dehon et al., 2002; Albert et al., 2003).

Locating the steepest part of the regression slopes essentially identifies this area of sudden change in electrical resistivity, and hence the interface between sapwood and heartwood.

The analysis code which was developed for this method (Appendix C) recreates an image of the cross section using a similar colour scale, by spatially interpolating the resistance values for each point coordinate. Bandwidth data are collected by rotating the shape about the geometric centre and gathering information in the horizontal and vertical planes a total of four times (the original shape, plus three rotations of 22.5°). This yields eight transects for each sample; a horizontal and vertical transect for each rotation. Once located, sapwood widths for each stained section were measured along the same radii as the ERT shape based on the interface of stained and non-stained wood. Bark thickness was measured using a digital Vernier calliper and a mean bark thickness (b) derived for each cross section. Figure 4.3 depicts the process pictorially for live oak sample QV-002 at 80 cm using the original shape.

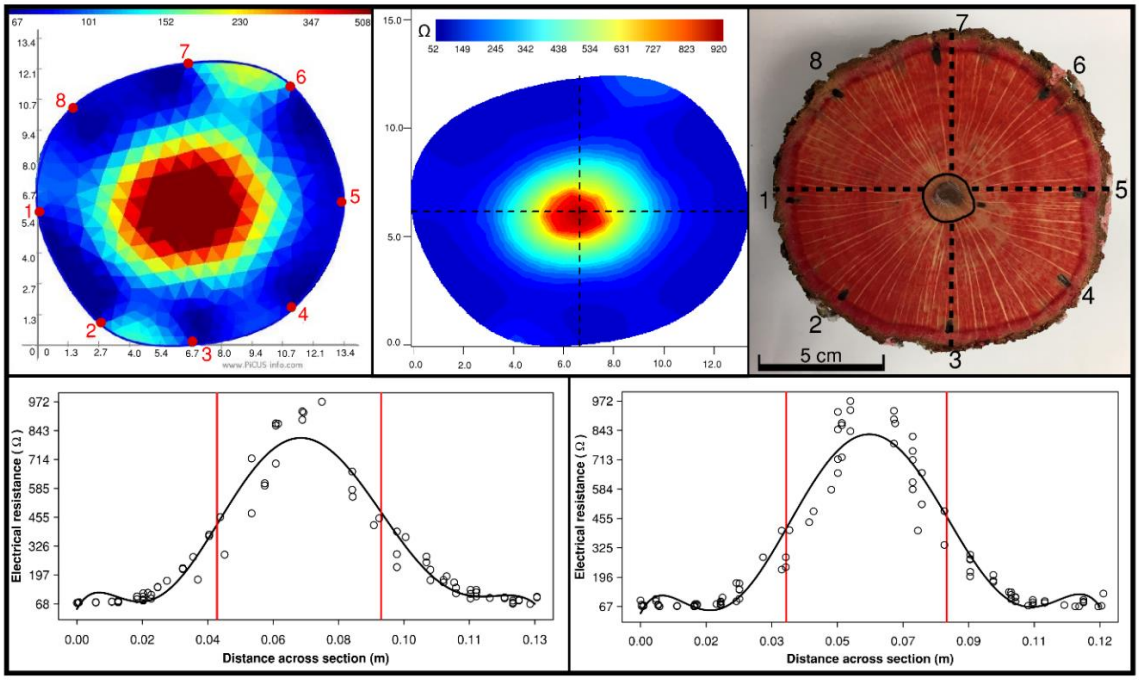

Figure 4.3: Example of ERT extraction tool and bandwidth analysis for live oak sample QV-002 at 80 cm for the original (unrotated) shape. Upper left: - ERT image. Numbered locations indicate electrode positions. Upper centre: - Data extraction plot and located bandwidth centres (dashed lines). Upper right: - Dissected live oak cross section showing located SW/HW boundary (solid line) and bandwidth centres (dashed lines). Lower left: - ERT data for bottom to top bandwidth. Lower right: - ERT data for left to right bandwidth. Red vertical lines represent the SW/HW boundary based on the steepest part of the slope.

4.3.5 Calculating sapwood area

Conductive sapwood areas for each sample were derived by analysing digital photographs of the stained sections using ImageJ image analysis software (Rasband, 2014). Stained areas of the images were isolated from those which were unstained and their areas (in cm^2) derived from scaled photographs. For ERT, the sapwood area of a single sector (a_{sw}) - defined as the area between bark and heartwood (a_{hw}; Equation 4.1) - was calculated using the mean of two adjacent radii (separated by 22.5°) with Equation 4.2. Total sapwood areas for each sample (A_{sw}) were calculated by summing the sapwood areas for each of the 16 sectors, created using an equivalent number of radii (Equation 4.3, Figure 4.4). Where other methods have estimated sapwood area by assuming radial uniformity of a sample using four (Guyot et al., 2013; Wang et al., 2016) or eight (Bieker and Rust, 2010b; Githiomi and Dougal, 2012) sapwood radii, i.e. a perfect cylinder based on a mean radius, this method better accounts for non-uniformity of the cross section. The results of each method for each cross section were then compared and regressions were developed for each species.

$$a_{hw} = \pi(r - b - r_{sw})^2 \times \frac{\varphi}{360} \quad \text{(Equation 4.1)}$$

$$a_{sw} = (\pi(r - b)^2 \times \frac{\varphi}{360}) - a_{hw} \quad \text{(Equation 4.2)}$$

$$A_{sw} = \sum a_{sw} \quad \text{(Equation 4.3)}$$

Where a_{sw} = the sapwood area of an individual sector (cm^2). a_{hw} = the heartwood area of an individual sector (cm^2). b = bark thickness (cm), r = the mean radius of two adjacent section radii (cm), r_{sw} = the mean sapwood radius of two adjacent sapwood radii (cm) and φ = 22.5°.

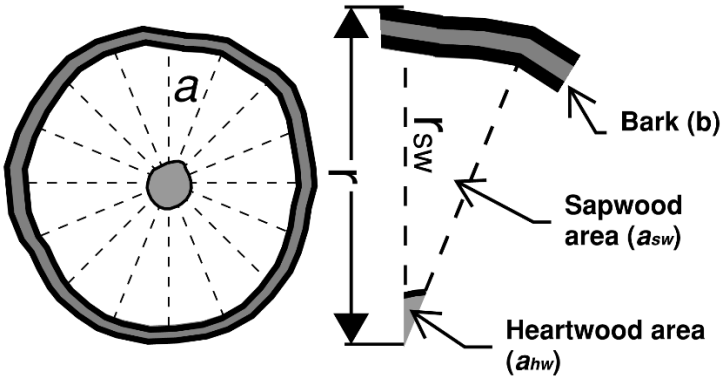

Figure 4.4: Diagrammatic representation of 16 sapwood radii (dashed lines) and bandwidth transects. The sector marked 'a' is enlarged to the right. r = the radius from the outer edge of the bark to the geometric centre and r_{sw} = the sapwood radius from the inner edge of the bark (b) to the heartwood interface.

4.3.6 Statistical analysis

Linear regression models were established using the lm() function in R (R Core Team, 2018) to compare the measured sapwood dimensions with the ERT estimated sapwood dimensions, using the ERT as the explanatory variable. Model accuracies were described using the coefficient of determination (R^2), p values as well as root mean square error (RMSE) and bias using the Metrics package for R (Hamner et al., 2018).

4.4 Results

4.4.1 Dye perfusions

Dye perfusions of ring porous wood showed a distinctive darkened band of stain in the most recent earlywood ring just beneath the bark / cambium, with the remaining stain becoming more mottled towards the centre of each section (Figure 4.3). Whilst it is generally accepted that the majority of sap flow in ring-porous species occurs in the outermost earlywood ring (Longman and Coutts, 1974; Ellmore and Ewers, 1986; Hoffman, 2012), the results of the dye perfusion testing show that other areas of the xylem tissue in *Q. nigra* and *Q. virginiana* remain conductive well beyond the outermost earlywood vessels, a trait previously observed in other *Quercus* species (Granier et al., 1994).

For diffuse wood, results of the dye-perfusion test revealed an interface between stained and non-stained wood, however greater negative pressure was required to draw the dye through the timber section; likely due to the narrower diameter of the vessel lumens of diffuse wood when compared to the ring porous species (Panshin and Zeeuw, 1980). This supports the notion that ring porous trees have a greater hydraulic efficiency than diffuse porous trees (McCulloh et al., 2010; Zanne et al., 2010).

4.4.2 Electrical resistance tomography

The results of the ERT revealed spatial heterogeneity in the resistivity profiles, with all analysed specimens having a central region of higher resistivity surrounded by a ring of lower values. These types of resistivity profiles produce Gaussian-shaped plots. Resistivity values for *Quercus virginiana* ranged from 26 to 1087 Ω, for *Q. nigra* values ranged from 33 to 543 Ω, and for *Acer rubrum* they ranged from 55 to 577 Ω. Typical resistivity profiles for each species are seen in Figure 4.5.

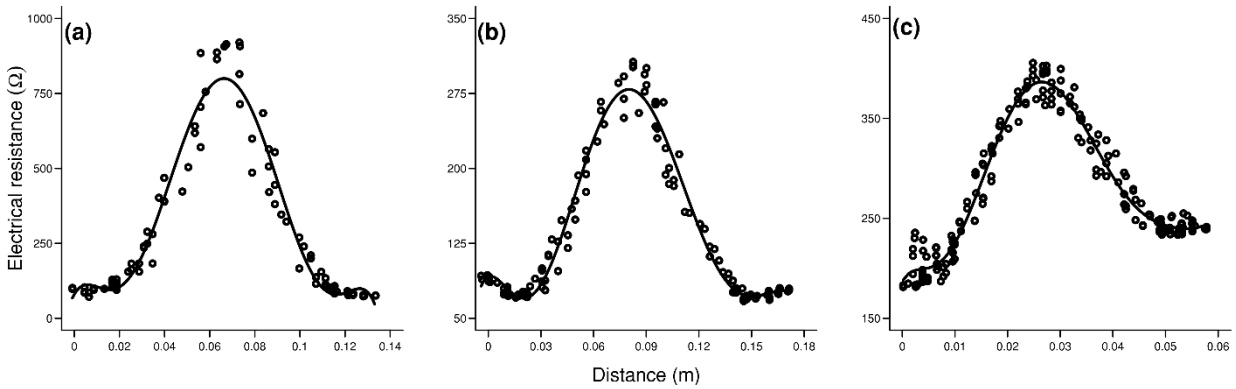

Figure 4.5: Example of electrical resistivity profiles in a 1 cm west to east bandwidth for (a), *Quercus virginiana*, (b), *Quercus nigra* and (c), *Acer rubrum.*

4.4.3 ERT sapwood estimation

Table 4.1 details the sapwood widths and areas for each measured sample along with its diameter and measuring height on the tree. Table 4.2 details the regression information relating to the various relationships between ERT estimates and measured values.

Sapwood widths for ring porous species were estimated by the ERT with comparable accuracy with RMSE values of 0.93 cm (27%) and 1.15 cm (27%) for *Q. virginiana* and *Q. nigra* respectively. Model bias varied considerably with values of 0.82 cm (26%) and 0.89 cm (19%). for *Q. virginiana* and *Q. nigra* respectively. ERT estimates of sapwood width for *Quercus virginiana* correlated strongly with measured values (R^2= 0.86). ERT was less able to predict sapwood widths in *Quercus nigra* (R^2 = 0.77), although the relationship was still significant ($p < 0.01$) (Figure 4.6(a), Table 4.2). ERT was less effective at predicting sapwood width in *A. rubrum* with RMSE and bias values of 1.92 cm (47%) and 1.85 cm (46%) respectively. Model strength was less than that for both *Quercus* species (R^2 = 0.73) (Figure 4.6(a), Table 4.2).

Sapwood areas were measured more accurately for *Q. virginiana* than for *Q. nigra* with RMSE values of 11.12 cm^2 (19%) and 25.98 cm^2 (33%) respectively. Model bias showed the same trend with values of -5.81 cm^2 (-6%) and -15.78 cm^2 (-27%) for *Q. virginiana* and *Q. nigra* respectively. Both models correlated well (R^2= 0.97 for *Q. virginiana* and 0.80 for *Q. nigra*) and slope coefficients were similar (*Q. virginiana* = 0.85, *Q. nigra* = 0.83) (Figure 4.6(b), Table 4.2). Sapwood area predictions yielded greater error in *A. rubrum* with RMSE and bias values of 33.52 cm^2 (131%) and -29.34 cm2 (-338%) respectively. Model strength was noticeably less than for the two oaks (R^2 = 0.56) (Figure 4.6(b), Table 4.2).

Figure 4.7 depicts the relationships between stem diameter and the measured (a) and ERT (b) sapwood areas for each of the investigated species.

Table 4.1: Characteristics of the investigated trees.

Prefix key: QV = *Quercus virginiana*, QN = *Quercus nigra*, AR = *Acer rubrum*

				Measured values		ERT values	
Tree ID	**Measuring height (cm)**	**Diameter (cm)**	**Mean bark thickness (cm)**	**Sapwood width (cm)**	**Sapwood area (cm^2)**	**Sapwood width (cm)**	**Sapwood area (cm^2)**
QV-001	120	16.87	1.03	4.95	136.78	4.33	139.76
	445	9.87	0.59	3.21	39.23	1.80	35.92
QV-002	35	15.12	0.96	3.86	86.41	3.22	97.89
	80	13.69	0.78	3.70	65.13	3.42	86.74
	115	13.37	0.79	4.01	79.66	3.60	92.62
	335	7.96	0.46	2.50	23.09	1.18	19.34
QV-003	60	16.23	0.97	5.35	117.39	4.37	138.43
	150	14.64	0.86	4.69	85.14	3.95	109.08
	330	8.28	0.56	2.26	20.43	1.63	22.40
QV-004	60	16.23	0.85	4.13	116.83	4.07	121.56
	150	15.12	0.87	4.58	102.33	3.91	113.11
	345	9.87	0.62	3.13	40.55	1.97	40.93
QV-005	170	9.87	0.51	2.39	30.90	2.07	33.95
	200	7.32	0.45	2.59	21.52	1.39	18.79
	325	10.19	0.63	3.16	53.45	2.22	48.42
QV-006	525	8.12	0.49	2.77	21.38	0.96	12.58
QV-007	220	10.50	0.66	3.18	42.37	2.74	58.40
	310	7.64	0.49	2.96	18.95	1.61	22.91
	360	7.32	0.48	2.10	21.20	1.50	20.30

Tree ID	Measuring height (cm)	Diameter (cm)	Mean bark thickness (cm)	Measured values		ERT values	
				Sapwood width (cm)	Sapwood area (cm^2)	Sapwood width (cm)	Sapwood area (cm^2)
QN-001	185	13.37	0.42	5.87	123.59	3.92	110.83
	130	13.85	0.43	4.42	97.02	3.37	103.51
	50	16.07	0.46	4.27	104.89	4.56	155.26
QN-002	300	7.16	0.39	2.06	19.61	1.67	23.37
QN-003	40	12.73	0.41	4.78	52.11	3.50	93.96
QN-004	45	16.55	0.84	6.17	132.47	4.64	143.77
QN-005	230	8.44	0.37	2.44	26.68	2.14	36.15
AR-001	160	12.73	0.35	5.14	59.30	3.06	89.92
	340	7.64	0.31	2.68	8.73	1.65	24.17
AR-002	210	13.37	0.31	4.84	13.77	2.53	75.89
AR-003	40	13.05	0.49	5.02	42.28	2.67	79.58
AR-004	170	11.94	0.38	3.54	52.39	2.37	65.23
	440	8.28	0.26	3.54	7.42	1.61	28.07
AR-005	90	10.19	0.37	4.36	2.71	2.01	44.99
	230	8.59	0.28	3.24	18.70	1.63	32.20

Table 4.2: Regression coefficients for sapwood width and sapwood area relationships. All regression formulae are in the format $y = ax + b$, where y = the measured value, and x = the ERT predicted value.

	Sapwood width					
Species	**a**	**b**	***R²***	**p**	***RMSE***	**Bias**
Quercus virginiana	0.76	1.44	0.86	<0.001	0.93 (27%)	0.82 (26%)
Quercus nigra	1.21	0.18	0.77	<0.01	1.15 (27%)	0.89 (19%)
Acer rubrum	1.43	0.90	0.73	<0.01	1.92 (47%)	1.85 (46%)

	Sapwood area					
Species	**a**	**b**	***R²***	**p**	***RMSE***	**Bias**
Quercus virginiana	0.85	3.82	0.97	<0.001	11.12 (19%)	-5.81 (-6%)
Quercus nigra	0.83	0.43	0.80	<0.01	25.98 (33%)	-15.78 (-27%)
Acer rubrum	0.65	9.86	0.56	0.03	33.52(131%)	-29.34 (-338%)

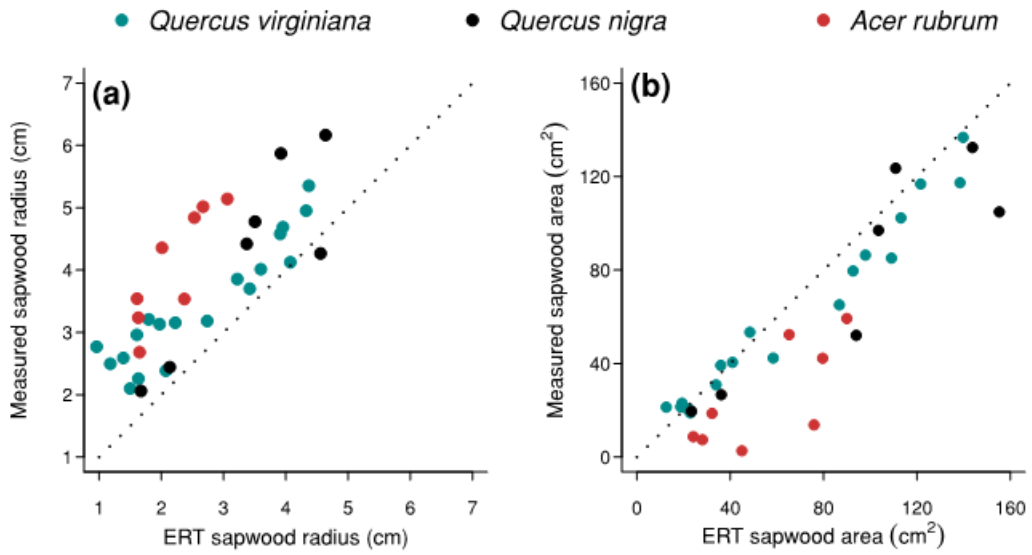

Figure 4.6: Relationships between ERT predicted and measured sapwood widths (a) and areas (b) for *Quercus virginiana*, *Quercus nigra* and *Acer rubrum*. Dashed lines are 1:1 lines.

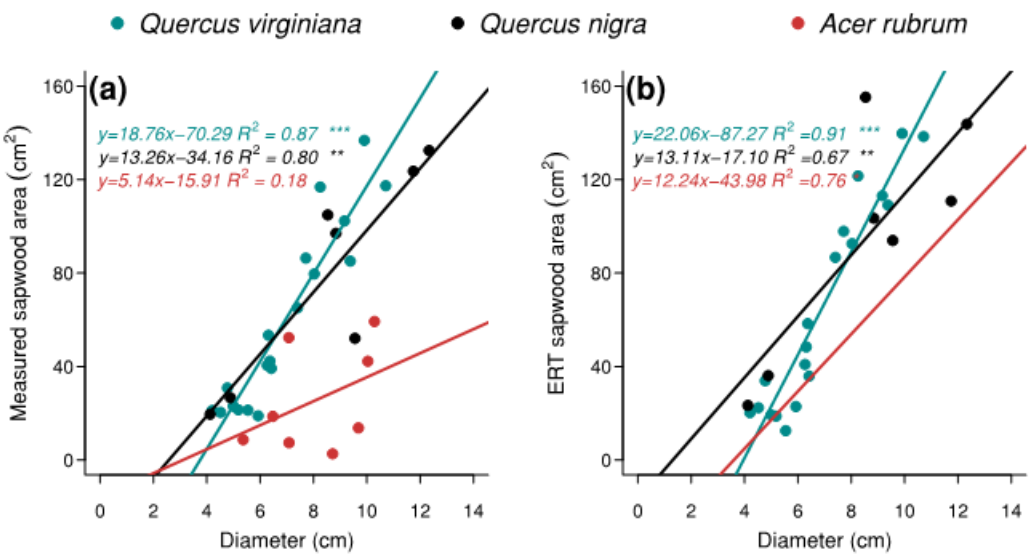

Figure 4.7: Relationships between stem diameter and measured sapwood area (a) and ERT sapwood area (b) for *Quercus virginiana*, *Quercus nigra* and *Acer rubrum.*

4.5 Discussion

Spatial variation in the resistivity profiles agreed well with the results from similar past works (Bieker and Rust, 2010b; Guyot et al., 2013; Wang et al., 2016). The range of resistivity values for *Q. virginiana* were comparable to those observed in other *Quercus* species (Bieker and Rust, 2010a). The range of resistivity values for *Q. nigra* was less, perhaps because of its riparian growing environment and the abundance of available soil moisture. Xylem lumens laden with water would be expected to produce lower resistivity values (Bieker and Rust, 2010b). Resistivity values for *A. rubrum* compared well with *Q. nigra*. Variation in the range of resistivity values between ring and diffuse porous wood was observed, as well as between species within the same genus, as was seen by previous investigations (Wang et al., 2016). This type of variation may be due to differing chemical wood composition (Shigo and Shigo, 1974; Kubo and Ataka, 1998; Meerts, 2002; Bieker and Rust, 2010a), and so resistivity values are likely to be both species dependent, as well as temporally influenced by seasonal changes in wood moisture content (Bieker and Rust, 2010b; Wang et al., 2016) and the presence of decay causing organisms (Bieker et al., 2010).

Negative model bias values for sapwood areas for each investigated species shows that ERT had a tendency to overestimate actual values. Model strength was similar to those established by Wang et al. (2016), whose study found that ERT marginally overestimated actual measured values for three diffuse porous Australian angiosperms. The work of Guyot et al. (2013) revealed that ERT was less effective at determining the SW/HW interface for a pine hybrid (*Pinus elliottii* Engelm var. *elliottii* × *Pinus caribaea* Morelet. var. *hondurensis*), however Bieker and Rust (2010b) found that ERT was effective for *Pinus sylvestris* L. when compared to staining. Differences in accuracy amongst species may be due to the chemical composition of the wood, or simply the validation method, since moisture content may change before extractive content in the heartwood reaches levels visible by staining or visual appraisal (Bieker and Rust, 2010b).

4.5.1 Practical applications and use of ERT

Besides its application for decay detection, ERT is an effective tool for estimating sapwood areas of trees. It takes approximately 15 – 30 minutes to undertake a single ERT analysis on a standing tree (Bieker and Rust, 2010b; Lin et al., 2012; Guyot et al., 2013), allowing for large numbers of trees to be non-destructively tested in a relatively short time frame. This may be advantageous and of particular use to replace destructive methods for developing allometric sapwood area equations (Vertessy et al., 1995; Gould and Harrington, 2008; Lubczynski et al., 2017a) based on trunk diameter (Figure 4.7) in line with the Pipe Model (Shinozaki et al., 1964a), or for stand level transpiration studies using sap flow probes (Wullschleger et al., 2001). The disadvantage of the technique is that the equipment is expensive (approximately US$10,000 including calliper) and may give erroneous results when used during periods of extreme wetness (Wang et al., 2016).

4.5.2 Technical notes

Sources of variation between ERT and actual values may lie in the geometric plotting of the cross section, since the values derived from ERT are dependent on the input dimensions. Inaccuracies during geometry plotting would likely be carried through the calculation process, and has been shown recently to be a major source of error for other types of tomography (sonic tomography) on standing trees (Rust, 2017). Users of the device for sapwood area determination should exercise care and ensure the dimensions of the cross section are recorded accurately to achieve best results.

When the method (Wang et al., 2016) was tested, it was apparent that although it is highly effective, the narrow (<1 cm) bandwidths extract an insufficient number of data points from the tomogram centres of large (>20 cm) diameter trees, owing to the large dimensions of the triangles in the central region. Accuracy of the ERT improves by increasing the number of electrodes, thereby reducing the spacing between them. Inference of resistivity data increases with increasing distance from the electrode pairs. The ERT infers the resistivity data in larger triangles with increasing distance from the electrodes, giving rise to a reduced number of data points in the narrower bandwidths. The R script developed for this method (Appendix C) extracts the resistivity data in bandwidths between 1 and 4 cm with a 1 cm resolution. These bandwidths were found to be effective at extracting a sufficient number of data points from both small and large trees.

Within the tomographic software, there are options to adjust mesh fineness (the number of triangles in the tomogram image). The default value is 4 with options increasing to 8. It is possible to increase the mesh fineness beyond 8 by manually inputting the value and this has the effect of increasing the number of triangles in the tomogram image. Although improving the accuracy of the tomographic information relies upon increasing the number of electrodes, increasing mesh fineness adds resolution to the image quality and increases the number of data points in the resistivity bandwidth. This may be useful when undertaking the analysis on large (≥50 cm diameter) trees where additional electrodes are not available and the circumferential electrode spacing increases.

The ERT employed in this study assumes the infinite continuation of the tree stem above and below the measuring level, and recommends that a minimum distance of clear trunk equivalent to the diameter at the measuring height is employed for tomographic analysis (Göcke, 2017). Insufficient lengths of clear trunk above and below the ERT level can give rise to artefacts, as too can incorrectly positioned electrodes (Oldenborger et al., 2005; Guyot et al., 2013). For this study, a minimum length of twice the trunk diameter was employed to minimise the appearance of artefacts.

A possible limitation to this method – and an important point to consider for those who choose to repeat it - is that accuracy of the ERT can vary under differing environmental conditions (Yue et al., 2018), and particularly following periods of rainfall when wood moisture content may increase as water becomes increasingly available (Wang et al., 2016). Since the resistivity of the cross section is closely related to wood moisture content (Bieker et al., 2010; Guyot et al., 2013; Bär et al., 2019), under wet conditions, wood moisture in both sapwood and heartwood would increase in comparison to those under drier conditions. The transition between wet and dry (sapwood and heartwood) migrates inwards, causing the ERT to detect the SW/HW interface further towards the pith than the actual positions (Wang et al., 2016), resulting in overestimations of the sapwood width. Ideally this study would have been conducted during a period of prolonged drought, e.g. two to three weeks of no rainfall. Given the wider temporal limitations of the thesis research, this was not possible and the ERT data were gathered at the start of the Florida rainy season (May to October), when daily precipitation events (often after 14:00) become increasingly common.

4.6 Conclusions

In this study, electrical resistance tomography was tested, and its effectiveness compared to dye-perfusions for detecting the sapwood - heartwood interface in order to estimate sapwood width and area for two ring-porous and one diffuse-porous species. It was found to be effective at identifying this boundary for *Quercus. virginiana* (R^2 = 0.86), *Quercus nigra* (R^2 = 0.77) and *Acer rubrum* (R^2 = 0.73) growing in Floridian conditions. Sapwood area was overestimated for all investigated species, however strong ($R^2 \geq$ 0.80) linear relationships were established between predicted ERT sapwood area and measured conductive sapwood area values for both *Quercus* species. The results of this study agree with other work and supports the use of ERT as an effective investigative tool in this field of research. An R script has been developed to analyse electrical resistivity data and estimate the sapwood - heartwood interface.

4.7 Epilogue

Applying ERT technology in this way is relatively new and with each new study the methods are improving. It was certainly advantageous to this thesis to be able to develop this method, to be later relied upon, but also in the context of the wider scientific community. The purpose of providing the R code sequence was to make this technology more widely available to other researchers, and to further improve its application in this field.

Chapter 5: Effects of root pruning on two species of *Acer* in New Zealand

The contents of this chapter have been reproduced from:
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5.1 Preamble

This investigation was undertaken using two species of *Acer* within New Zealand. It was designed and planned prior to the knowledge that financial support would facilitate a trip to Florida to undertake further investigations, although the application for funding had been made.

The purpose of this investigation was to investigate the allometric hypotheses and to answer research questions numbers 1 and 5.

Research question 1: What effect will an increasing number of trenches in which roots are severed have on tree growth and physiology?

Research question 5: Can the allometric relationship between trunk and root cross-sectional area be used as a tool to quantify a root pruning threshold above which negative effects are avoided?

The materials and methods section in this chapter has been edited from its original form to avoid repetition of the methods previously described in section 3.2.

5.2 Introduction

Successfully integrating trees into the built environment is a major challenge for creating high-value urban forests (Bartens et al., 2010). Urban trees are continually exposed to the rigours and challenges of sharing their environment with anthropogenic intervention (Koeser et al., 2013), which may be present from the early stages of nursery development, and can affect tree health and reduce longevity (Watson et al., 2014).

Once established, trees alongside roads or in parks can have their root systems affected by construction work such as utility installation and maintenance (Thomson and Rumsey, 1997) or pavement repair (North et al., 2017). Typically, engineering requirements take precedence over tree conservation (Baines, 1994; Jim, 2003). Whilst it is possible to manage these conflicts in a variety of ways (Morgenroth, 2008), they frequently result in the damage or complete removal of tree roots (Baines, 1994; Čermák et al., 2000; Jim, 2003). Root severance can negatively affect tree stability (Hamilton, 1988; Smiley, 2008; Ghani et al., 2009; Smiley et al., 2014), growth (Ferree, 1992; Miller and Neely, 1994; Khan et al., 1998; Wajja-Musukwe et al., 2008; Pretzsch et al., 2016) and vitality (Hauer et al., 1994; Watson, 1998). Furthermore, root pruning essentially induces water stress (Fini et al., 2013b), leading to perturbations of physiological processes (Dong et al., 2016).

Among the earliest of responses to water stress is the closure of stomatal apertures, which may result from dehydrating roots (Schulze, 1986; Liu et al., 2001b) mediated by chemical signalling (Davies and Zhang, 1991). Closing stomatal openings limits water loss through transpiration and protects other plant tissues from dehydration, by maintaining turgor and limiting cavitation (Chaves et al., 2003). Photosynthetic inhibition due to stomatal limitation is more closely related to soil-water status than to leaf water potential, suggesting that stomatal closure is more affected by available (soil) water levels than leaf dehydration (Chaves et al., 2002; Rouhi et al., 2007)

Chlorophyll fluorescence (CF) can provide valuable insights into the state of the photosynthetic mechanism and has been shown to be a useful tool for plant stress detection (Epron et al., 1992; Maxwell and Johnson, 2000; Percival, 2005; Arend et al., 2013; Guha et al., 2013). CF investigations are a quick, easy to use, non-destructive method to gain insights into the physiological state of plants both in the laboratory, and in the field (Flexas et al., 2000). The variable fluorescence parameter, Fv/Fm, reveals information about the maximum potential quantum efficiency of the photosystem 2 (PSII) apparatus, and has been used as a reliable indicator of plant stress (Maxwell and Johnson, 2000). Typical values of Fv/Fm in unstressed leaves of most plants are ≈ 0.75 - 0.83 (Krause, 1991; Maxwell and Johnson, 2000). Changes in the value of Fv/Fm may be due to a change in the efficiency of non-photochemical processes (Maxwell and Johnson, 2000), and in particular, photo-inhibition, which can happen when proteins (particularly the D1 protein) in the PSII apparatus are damaged through photo-oxidation during stomatal closure (Powles, 1984; Long et al., 1994; Ort, 2001; Keren and Krieger-Liszkay, 2011).

Traditional investigations into tree responses to root severance involve an indiscriminate approach to root removal, by severing all roots in one or more trenches (Watson, 1998; Smiley, 2008; Fini et al., 2013b; Pretzsch et al., 2016). Although root loss for individual trees may not be fully quantified, the results of these studies provide useful tools for the practitioner during large-scale developments, where these types of ground alterations are involved; for example, linear excavations such as those which might be associated with a new road or building foundation.

However, physical impediments to rooting (such as pavements and buildings) may alter root system architecture in the urban environment (Čermák et al., 2000) and these tools may not be as effective. Localised disturbances to root systems - such as during the installation of new street furniture (for example, seating, signage, or light poles) or isolated utility repair - may involve only minor excavations with a more discriminate, or selective approach to root removal, and the practitioner may need to rely on other tools to assist in their decision making when removing roots. Although some work has been done to investigate the effects on trees to root pruning, the consequences have not been extensively studied, and more research is needed to determine specific practices (Costello et al., 2017).

Trunk diameter has been shown to be a reasonably reliable predictor of root system spread (Tubbs, 1977; Gilman, 1989; Gerhold and Johnson, 2003; Day et al., 2010) and is often employed to establish a "tree protection zone" where large-scale developments are involved (Harris et al., 2004; Standards Australia, 2009; British Standards Institute, 2012; Fite and Smiley, 2016). The tree protection zone is a circular area of ground around the trunk with a radius derived as factor of trunk diameter; often this is a factor of 12. The allometric principles of this approach may stem from the pipe model theory of tree form (Shinozaki et al., 1964a, b), which primarily relates to the relationship between the cross-sectional area of conductive sapwood in the trunk, and canopy leaf area (Shinozaki et al., 1964a; Vertessy et al., 1995; Grabosky et al., 2007; Gould and Harrington, 2008). However, cross-sectional area relationships between trunk and root systems have also been observed (Shinozaki et al., 1964b; Kaipiainen and Hari, 1985; Carlson and Harrington, 1987; Kuiper and Coutts, 1992; Rodtassana and Poungparn, 2012).

Owing to increasing cross-sectional areas, larger diameter roots have a greater mechanical (Coutts, 1983; Coutts, 1987; Danjon et al., 2005; Coder, 2010) and functional (Tyree, 2003; Schuldt et al., 2013; Meunier et al., 2017) contribution to tree longevity (stability and hydraulic function respectively). Previous work has revealed significant correlations between the force required to pull standing trees to one degree, and the ratio of severed root cross-sectional area (CSA) to trunk CSA ($\sum$(severed root CSA) / trunk CSA at 1.37 m) (Smiley et al., 2014), however the relationship between this allometric variable and tree function (growth and physiology) has not been explored.

The aims of this study, therefore, were to:

- Investigate the effects of root pruning on the growth and physiology of two species of *Acer*, by quantifying root pruning doses using allometry.
- Take the first steps towards developing a practical tool for arboricultural practitioners who make day-to-day tree management decisions relating to roots and root care practices.

5.3 Materials and Methods

5.3.1 Study sites and trees

The study consisted of two experimental sites in the Waikato region of New Zealand's North Island. Site 1 (37° 48' 37.85" S. 175° 24' 56.61" E, mean annual rainfall = 1,150 mm) was a commercial nursery specialising in field grown *Acer* varieties. One hundred *Acer palmatum* 'Bloodgood'. Thunb (mean DBH = 6.83 cm, standard deviation (δ) = 0.97 cm) grafted onto *A. palmatum* rootstock were randomly selected from a single block of 201 individuals planted in a sandy loam soil (mean bulk density = 0.81 g/cm^3 (δ = 0.07 g/cm^3, n = 8)) in 2010 from 45 litre containers. Trees were spaced 4 m between rows and 2 m along rows. No undercutting or conditioning had been undertaken since planting.

Site 2 (37° 44' 43.31" S. 175° 15' 0.01" E mean annual rainfall = 1,200 mm) was a publicly managed passive recreation reserve. A group of 19 *Acer negundo*. L (mean DBH = 11.73 cm, δ = 3.25 cm) planted in a sandy clay-loam soil (mean bulk density = 0.92 g/cm^3 (δ = 0.06 g/cm^3, n = 4)) in 2010 from 45 litre containers were selected for inclusion in the study. The trees were growing in a linear arrangement spaced approximately 4 m apart and had not been undercut or manipulated since planting.

Meteorological data were obtained using a virtual climate station (VCS) service (NIWA, N.D). The VCS produces daily meteorological estimates based on the spatial interpolation of actual data observations made at climate stations located around the country. Figure 5.1 depicts minimum and maximum daily temperatures as well as total daily rainfall for both sites based on the VCS data.

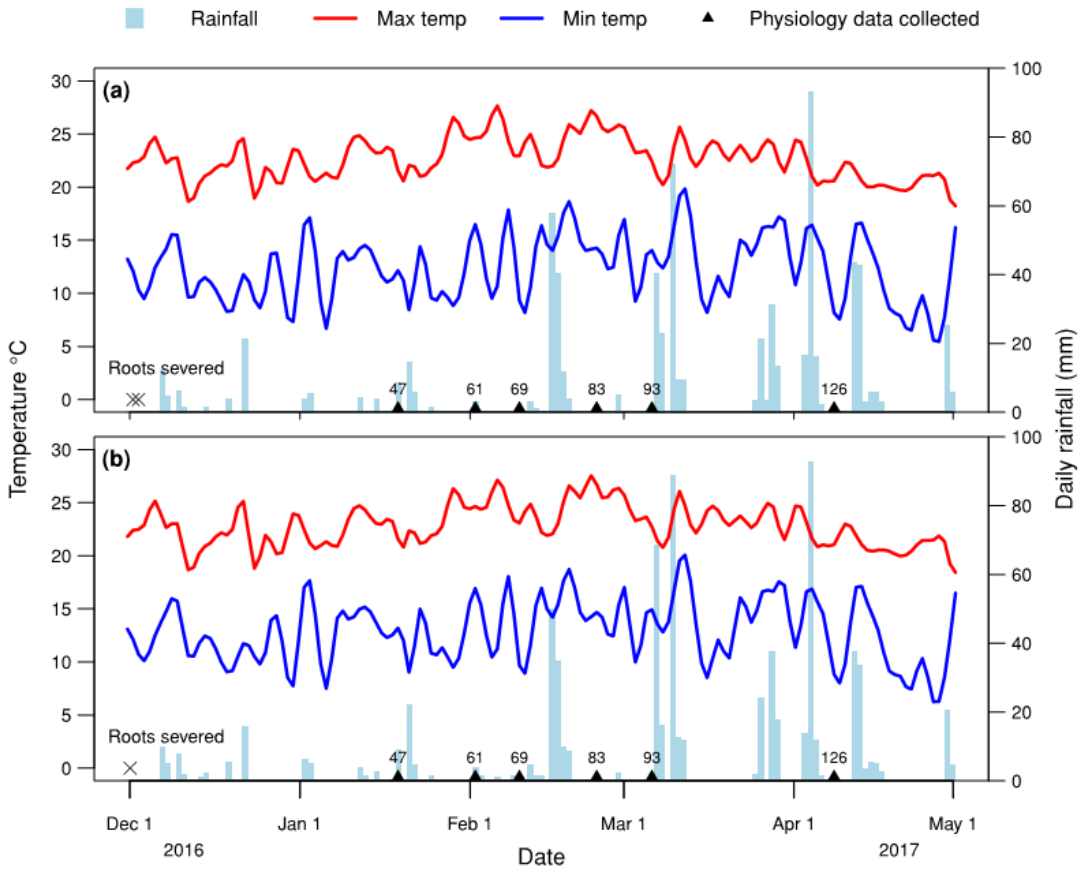

Figure 5.1: Meteorological conditions for Site 1 (a) and Site 2 (b) throughout the experimental period using VCS data. Triangles denote days on which physiological data were gathered with corresponding numbering denoting the number of days following root severance.

5.3.2 Root pruning treatments

Trees at each study site were randomly assigned to one of five treatment groups. Control (no root pruning), T1 (a trench on one side of the tree), T2, (parallel trenches on two sides of the tree), T3 (a trench on three sides of the tree) or T4 (a trench on four sides of the tree). Trenches 500 mm deep, 100 mm wide and 1.5 m long (except where they intersected) were excavated using pneumatic soil displacement (Air Spade, Guardair, Chicopee, MA, USA), 30 cm from the base of each tree. Roots spanning the trenches were severed manually using hand tools and fragments of each root were completely excised before filling in the trenches with the original soil material. Roots were severed at Site 1 on the 2nd and 3rd of December 2016 and at Site 2 on the 1st December 2016. Following root removal, root cross-sectional area ratios at 1.4 m ($Ar_{(BH)}$) and at ground level ($Ar_{(GL)}$) were determined using Equations 3.1 to 3.3 inclusive.

5.3.3 Sapwood area determination

Conductive sapwood area for both species was determined using microscopy techniques (Githiomi and Dougal, 2012) (Nikon SMZ-1B at 30 x magnification (Nikon, Tokyo, Japan)). Trees at Site 1 were felled immediately following the experiment and thin (≈ 50 mm) discs were harvested from the trunks. At Site 2, two 5 mm diameter increment cores were extracted; samples were taken as close to ground level as possible, and also at 1.4 m. Discs were sanded smooth and halved in the tangential direction ensuring that the pith was intersected. The axial face of the cut surface was visually inspected for vessel blockages associated with heartwood formation (De Micco et al., 2016). Conductive sapwood in the wood cores was again ascertained using microscopy techniques inspecting the cores for vessel blockages. The measurements of both sets of samples were used to derive heartwood diameters and the mean heartwood diameter for each tree at each height was then used to estimate the heartwood area. Heartwood area was then subtracted from the total stem cross-sectional area to give trunk conductive sapwood area. Root cross-sectional areas were then expressed again as a proportion of the conductive sapwood area to establish a sapwood area ratio ($As_{(x)}$) using Equation 3.4.

5.3.4 Tree responses to root pruning - Physiology

As with other mesophytic *Acer* species, the expectation was for the subject species to respond isohydrically to the root loss-induced water stress (Roman et al., 2015; Yi et al., 2017). That is; it was expected to see stomatal closure (Liu et al., 2001b; Medrano et al., 2002) and perturbations of the photosynthetic mechanism (Powles, 1984; Flexas et al., 1999; Lu and Zhang, 1999; Ashraf and Harris, 2013) following exposure to water deficit (root removal).

Stomatal conductance and chlorophyll fluorescence measurements were taken periodically (approximately fortnightly pending favourable meteorological conditions) at both sites throughout the growing season (January to April) from three fully expanded sun leaves per tree.

The dark adaptation period was 45 minutes and the same leaves were used for both conductance and fluorescence measurements throughout the data gathering exercise. Conductance measurements were made using an SC-1 leaf porometer (Meter Environment (formerly decagon Devices), Washington, USA) calibrated to local conditions using the SC-1 Leaf Porometer Calibration Kit (part# 30425, Meter Environment, Washington, USA) supplied by the manufacturer and following the manufacturer's instructions. Fluorescence measurements were made using a Walz Mini-Pam fluorescence yield analyser (WALZ GmBH, Germany). Measurements were gathered in the morning between 08:00 and 11:00 and again in the afternoon between 14:00 and 17:00. Morning and afternoon data were combined and averaged to give mean daily conductance / fluorescence values for each tree. A randomly selected subset of 50 trees (10 replicates of each treatment) at Site 1 were used for physiological measurements to ensure all measurements were made within the specified measurement periods. Conductance measurements were taken independently of fluorescence measurements, with a 24-hour separation using the same leaves on each tree. At Site 2, fluorescence and conductance data were gathered simultaneously. Conductance readings were taken from the tip of the terminal leaflet of each tree, and fluorescence readings were taken approximately 35 mm proximal to the conductance location, so that the dark adaptation process did not interfere with the conductance reading. Conductance readings are absent from both sites on day 47, due to a device calibration error.

5.3.5 Tree responses to root pruning – Tree growth

Trunk diameters at ground level and at 1.4 m were recorded immediately prior to root severance treatments and again at the end of the experimental period (April 2017). Trunk area growth rate (TGR) was then expressed as $\ln(cm^2)\ day^{-1}$ (Contreras et al., 2011) using Equation 5.1. New shoot extension was measured using 18 new terminal shoots per tree per treatment. Leaf area was measured using ten sun leaves harvested from the third node proximal to the terminus of an equivalent number of twigs from each tree per treatment using an LI-3100C leaf area meter (LI-COR Devices, Nebraska, USA). Twigs and leaves were harvested from non-shaded regions which may produce abnormally elongated twigs.

$$TGR = \frac{(ln(diameter_{end}) - ln(diameter_{start}))}{number\ of\ days\ since\ root\ pruning} \quad \text{(Equation 5.1)}$$

5.3.6 Tree condition rating

At the end of the experiment, the condition of each tree was visually assessed to examine the extent of the visibly manifested signs of root severance, i.e. the extent of the dieback / defoliation. A 'condition rating' (*Cr*) adapted from the work of others (Watson, 1998; Tóth et al., 2015) was assigned to each tree (Table 5.1). All trees had a condition rating of 0 at the start of the study.

Table 5.1: Condition rating description of visual symptoms of root severance effects.

Condition rating	Description
0	No symptoms
1	1% to 25% defoliation/dieback
2	26 to 50% defoliation/dieback
3	51 to 75% defoliation/dieback
4	76% to 99% defoliation/dieback
5	100% defoliation/dieback

5.3.7 Statistical analyses

5.3.7.1 Treatment effects

All data were analysed using R statistical software version 3.4.4 (R Core Team, 2018). Because of the confounding influence of geographical differences, and differences in tree size, each site was analysed separately. One-way ANOVA were employed to test for significant differences in response to the root pruning treatments. Post-hoc Tukey HSD tests were used for pairwise comparisons of significance between treatments. For the categorical *Cr* response data, Kruskal–Wallis tests were undertaken with post-hoc Dunn's tests specifying Bonferroni p adjustment with the "dunn.test" package (Dinno, 2017).

5.3.7.2 Continuous variables

Linear regression models were fitted to physiological and morphological response data using root cross-sectional area ratios ($Ar_{(x)}$ and $As_{(x)}$) as the explanatory variables with the lm() function in R. For the categorical *Cr* response, proportional odds models were established using the clm() function in the "ordinal" package (Christensen, 2018), using $Ar_{(x)}$ as the explanatory variable.

5.3.7.3 Covariates

A distance dependent competition factor (Hegyi, 1974) using the nearest adjacent tree in each 45 degree azimuth (n = 3 to 8) was established for trees at Site 1 and introduced into the analytical models as a covariate, to control for the influence of adjacent trees on the growth response.

Unless otherwise indicated, all tests for significance are reported at $p \leq 0.05$.

5.4 Results and discussion

5.4.1 Sapwood areas

The microscopic analyses revealed that *A. palmatum* had no heartwood, and that the entire cross section of the tree stems at each investigated height were conductive right up to the pith. Henceforth, $Ar_{(x)}$ ratios for *A. palmatum* can be interpreted as $As_{(x)}$ ratios. *A. negundo* had heartwood present and the analyses revealed that portions of each tree's stem cross section were non-conductive. Accordingly, $As_{(x)}$ ratios are distinct from $Ar_{(x)}$ ratios for *A. negundo*.

5.4.2 Root cross-sectional area ratios

For both species, $Ar_{(x)}$ and $As_{(x)}$ values increased from T1 through to T4, showing that as the number of trenches increased, a larger area of roots relative to trunk area was severed. Total severed root cross-sectional areas were between 0.32 and 0.83 times the trunk cross-sectional area at 1.4 m ($Ar_{(BH)}$) for *A. palmatum*, while it ranged from 0.25 to 0.98 for *A. negundo*. Mean values for $Ar_{(BH)}$ and $As_{(BH)}$ ratios plus or minus one standard error (in parentheses) are presented in Table 5.2.

A potential downfall of using $Ar_{(GL)}$ as the explanatory variable, is that in many urban sites throughout New Zealand, urban trees receive injuries resulting from lawn maintenance equipment such as lawn mowers and line trimmers (Morgenroth et al., 2015). At Site 2, damage to the bases of the trees consistent with abrasions from line trimmers was observed for some trees. The resulting callus tissue and localised trunk irregularities may have yielded minor inaccuracies in the circumferential measurements at ground level, which would of course carry over to the cross-sectional area estimates giving rise to small errors. Henceforth, only $Ar_{(BH)}$ and $As_{(BH)}$ values are reported as explanatory variables.

Table 5.2: Mean $Ar_{(x)}$ and $As_{(x)}$ ratios for each root pruning treatment at each site ± one standard error (in parentheses). For each species, different letters in a single column denote a significant difference between treatments.

Species	Treatment	$Ar_{(BH)}$	$As_{(BH)}$
Acer palmatum 'Bloodgood'	T1	0.32 (0.04) a	-
	T2	0.62 (0.05) b	-
	T3	0.75 (0.06) b	-
	T4	0.83 (0.07) b	-
Acer negundo	T1	0.25 (0.06) a	0.29 (0.08) a
	T2	0.55 (0.09) ab	0.56 (0.09) ab
	T3	0.90 (0.13) b	0.92 (0.14) b
	T4	0.98 (0.22) b	0.99 (0.22) b

5.4.3 Physiological responses to root pruning

5.4.3.1 Stomatal conductance

For *A. palmatum* (Figure 5.2a(i)), the stomatal conductance response varied by treatment. Significant differences in the stomatal conductance response between all root pruning treatments and the control were observed, 61 and 69 days after roots were cut, though no difference existed when measurements were taken on day 83. Significant differences between the T4 treatment (mean $Ar_{(BH)}$ = 0.83) and control trees were sustained beyond day 83, and into the latter stages of the experiment. The results of the ANOVA significance tests are presented in Table 5.3.

For *A. negundo* (Figure 5.2a(ii)), the conductance response also varied by treatment, and each differed significantly from control trees 61 days following root pruning. At 69 days, only T3 and T4 differed from control trees. Treated trees generally continued to have lower g_s than control trees on days 83 and 93, though when data were gathered 126 days after root severance, no significant differences between treatment and control were observed.

The increase in stomatal conductance for treated trees of both species on day 83 appears to coincide with an increase in precipitation (Figure 5.1). In the absence of ground water recharge, root pruned trees were likely more predisposed to the effects of water stress (Fini et al., 2009; Fini et al., 2013b; Tóth et al., 2015; Dong et al., 2016), manifesting as reduced stomatal conductance values. The reducing number of statistical differences in stomatal conductance amongst treated and control trees at both sites could be due to a). late season precipitation alleviating the water stress, b). a sufficient number of newly grown roots were able to contribute to hydrological demands or c). a combination of the two (a and b).

5.4.3.2 Chlorophyll fluorescence (Fv/Fm)

No significant differences between treatment and control for the Fv/Fm response were observed for either species (Figure 5.2b), although on day 69, the T4 treatment for *A. negundo* differed from the T2 treatment (Figure 5.2b(ii)). With regards to *A. palmatum,* the absence of significant differences may be due, in part, to the presence of cyanic compounds in the mesophyll layer of the red leaves. Anthocyanins have been shown recently to provide a photoprotective function in other red-leaved *Acer* species (Fini et al., 2017).

For *A. negundo,* the range of Fv/Fm values was much broader, which may be due in part to the increased cross-sectional area of roots removed relative to the trunk area ($Ar_{(BH)}$), owing to the trees' larger DBH. Furthermore, *A. negundo* is a riparian tree in its native range (Maeglin and Ohmann, 1973), likely making it more predisposed to the negative physiological effects of water stress than a species more naturalised in drier environments.

Providing the water stress is insufficiently severe, electron flow downstream of the PSII centre is able to persist during periods of water stress-induced stomatal closure (Flexas et al., 1999), by recycling photorespiratory CO_2 (Takeba and Kozaki, 1998). Thus, even when carbon assimilation is curtailed, electron transport through the primary photochemistry is able to continue, and the fluorescence response may not reveal any photochemical anomalies; at least in the short term.

Furthermore, downregulation of photochemical activity may be alleviated by irrigation, avoiding the photo-inhibitory effects of root loss-induced water stress (Flexas et al., 1998). Analysis of historical meteorological data reveals that the growing season in which the study was undertaken experienced the most precipitation since the trees were planted, and so soil water availability would unlikely have been a contributing factor to the water stress.

Thus, the absence of significant differences in the Fv/Fm response for each species is likely due to a). interspecific differences in physiology / site conditions, b). an insufficient amount of root severance to induce a water stress-initiated fluorescence response, c). sufficient availability of soil water to alleviate the water stress effects, d). a combination of all factors (a, b and c) or e). in the case of *A. negundo*, an insufficient number of replicates.

Table 5.3: Results of one-way ANOVA significance tests for stomatal conductance (g_s) (m mol m^{-2} s^{-1}) and maximum photosystem II photochemical efficiency (Fv/Fm) responses following root pruning. Significance codes. * $p \leq 0.05$ ** $p \leq 0.01$ *** $p \leq 0.001$

Species	**Response**	**Days since root severance**					
		47	**61**	**69**	**83**	**93**	**126**
Acer palmatum 'Bloodgood'	*gs*	-	**	***	n.s	*	*
	Fv/Fm	n.s	n.s	n.s	n.s	n.s	n.s
Acer negundo	*gs*	-	***	***	**	**	n.s
	Fv/Fm	n.s	n.s	*	n.s	n.s	n.s

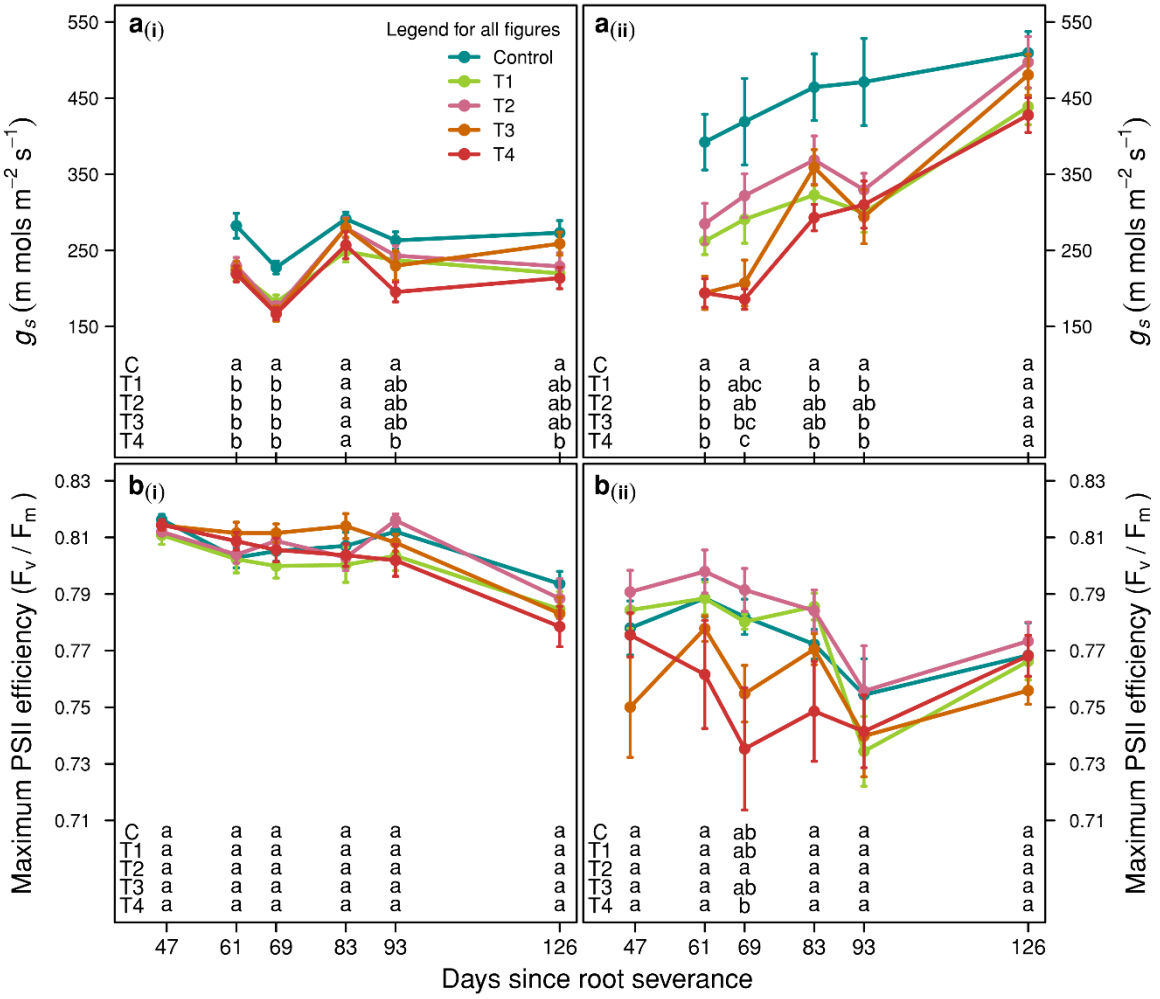

Figure 5.2: Treatment mean stomatal conductance (g_s) in m mol m^{-2} s^{-1} (a) and maximum photosystem II quantum efficiency (Fv/Fm) (b); plotted against number of days since roots were severed for *A. palmatum* (i) and *A. negundo* (ii). Tukey HSD results are shown in the matrix inset into each plot. Different letters in a single column denote significant differences between treatments (left hand side) on a particular day. Error bars show ± one standard error.

5.4.4 Tree growth response to root pruning

For each species, growth response varied by treatment. Figure 5.3 depicts bar plots of the growth responses and final condition rating for both species, mean values are included in Table 5.4. Reductions in shoot extension and leaf area were uniformly observed between all treatments and control for *A. palmatum*. TGR was only significantly lower for T4 trees. The results suggest that the negative effects of root pruning on the above-ground growth of *A. palmatum* emerge at the T1 treatment, when the severed root cross-sectional area was only 32% of the trunk cross-sectional area (mean $Ar_{(BH)}$ = 0.32). Treatment-related growth differences in *A. negundo* were not as widespread, with only TGR being significantly affected for trees beginning at the T2 treatment (mean $Ar_{(BH)}$ = 0.55).

The effects observed in trunk growth and shoot extension agree with those of others (Watson, 1998; Fini et al., 2013b; Pretzsch et al., 2016). Reductions in above-ground growth may result from preferential allocation of photoassimilates to the roots to compensate for the damage resulting from root severance (Rook, 1971; Hamilton, 1988; Amoroso et al., 2010a; Amoroso et al., 2010b). Reducing leaf area in response to root removal essentially reduces the transpirational surface area with a concomitant reduction in overall water loss (Liu and Stützel, 2004; Pallardy, 2008). This type of adaptive response to water stress may be an important survival strategy during abiotic stress.

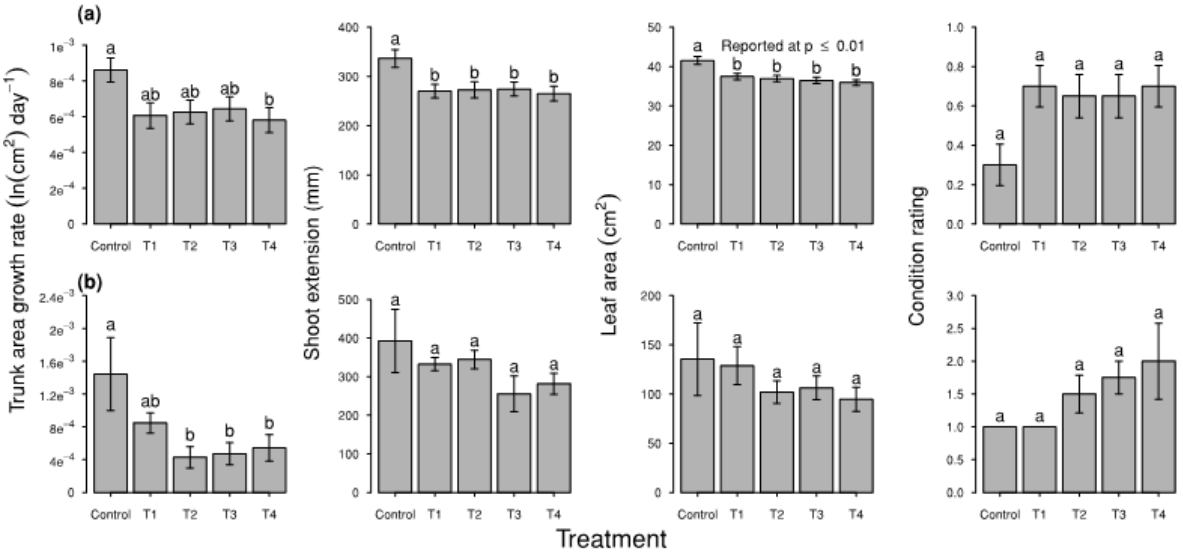

Figure 5.3: Bar plots showing growth and condition rating (*Cr*) responses for each treatment for *A. palmatum* (a, upper row) and *A. negundo* (b, lower row). *Cr*:- 0 = 0% dieback. 1 = 1%-25% dieback. 2 = 26%-50% dieback. 3 = 51%-75% dieback. 4 = 76%-99% dieback. 5 = 100% dieback. Error bars show ± one standard error.

Table 5.4: Mean values for trunk area growth rate at 1.4 m (TGR) (ln(cm^2 day^{-1})), shoot extension (mm), leaf area (cm^2) and condition rating for each treatment and each species following root severance treatments. Significance codes. * $p \leq 0.05$ ** $p \leq 0.01$ *** $p \leq 0.001$

Species	Treatment	TGR (ln(cm^2 day^{-1}))	Shoot extension (mm)	Leaf area (cm^2)	Condition rating
Acer palmatum 'Bloodgood'	Control	$8.6x10^{-4}$	336.60	41.54	0.30
	T1	$6.1x10^{-4}$	270.03	37.47	0.70
	T2	$6.3x10^{-4}$	272.64	36.97	0.65
	T3	$6.4x10^{-4}$	274.34	36.47	0.65
	T4	$5.8x10^{-4}$	265.17	35.94	0.70
Effect of treatment		*	**	***	n.s
Acer negundo	Control	$1.4x10^{-3}$	392.81	135.42	1.00
	T1	$8.5x10^{-4}$	332.56	128.81	1.00
	T2	$4.3x10^{-4}$	344.64	102.04	1.50
	T3	$4.7x10^{-4}$	255.39	106.21	1.75
	T4	$5.4x10^{-4}$	281.51	94.72	2.00
Effect of treatment		*	n.s	n.s	n.s

Condition rating was not significantly affected although a general trend towards premature canopy defoliation in both species was observed. *A. negundo* responded with a broader range of visual cues to suggest that vitality had been negatively affected more severely (Figure 5.3b). This may be due to interspecific differences in natural environments. Where *A. negundo* is a typically riparian tree, favouring moist conditions (Maeglin and Ohmann, 1973), *A. palmatum* is a sub-canopy forest tree, distributed in relatively drier conditions at higher altitude (Chang, 1990; Wada and Ribbens, 1997). It is moderately tolerant to drought stress (Gilman, 2014), possibly making this species better equipped for transient periods of water shortage.

5.4.5 The use of allometry as an investigative tool

Table 5.5 and Table 5.6 show regression statistics for linear models using $Ar_{(BH)}$ to predict physiology and growth responses respectively. Figure 5.4 depicts physiological responses to root pruning using seasonal mean data and $Ar_{(BH)}$ as the explanatory variable. Mean data were established using the arithmetic mean of all physiology data gathered for each tree of each species throughout the study. Model significance for each relationship for each species varied. Significant relationships between $Ar_{(BH)}$ and g_s responses were observed for *A. palmatum*, but not for the fluorescence variable (Fv/Fm). Significant relationships between $Ar_{(BH)}$ and each of the physiological response variables were observed for *A. negundo* on one of more measuring days, although the respective R^2 values ranged from 0.24 to 0.56.

$Ar_{(BH)}$ was more useful for predicting physiology responses in *A. negundo*, highlighting that tree physiology is highly dynamic and that there are clear differences in the way these two species have responded to the root pruning treatments at each of the sites. Model trends (slopes) generally follow the same pattern as the treatment effect responses (Figure 5.2), whereby increasing root pruning treatments yields greater response.

Table 5.5: Regression statistics for linear models using $Ar_{(BH)}$ to explain differences in stomatal conductance (g_s) in m mol m^{-2} s^{-1} and maximum photosystem II photochemical efficiency (Fv/Fm) responses. Significance codes. * $p \leq 0.05$ ** $p \leq 0.01$ *** $p \leq 0.001$

Species	Response	Statistic	Days since root severance						
			47	**61**	**69**	**83**	**93**	**126**	**Mean**
Acer palmatum 'Bloodgood'	*gs*	R^2	-	0.07	0.16	<0.01	<0.01	0.01	0.04
		Model significance	-	n.s	**	n.s	n.s	n.s	n.s
	Fv/Fm	R^2	0.01	0.01	0.01	0.02	0.04	0.01	0.01
		Model significance	n.s	n.s	n.s	n.s	n.s	n.s	n.s
Acer negundo	*gs*	R^2	-	0.56	0.46	0.19	0.24	0.08	0.40
		Model significance	-	***	**	n.s	*	n.s	**
	Fv/Fm	R^2	0.01	0.08	0.30	<0.01	<0.01	0.04	0.08
		Model significance	n.s	n.s	*	n.s	n.s	n.s	n.s

Figure 5.5 depicts growth response variables and condition rating data using $Ar_{(BH)}$ as the explanatory variable. The relationship between leaf area and $Ar_{(BH)}$ was highly significant ($p < 0.001$) (Figure 5.5c) in *A. palmatum*, but not TGR (Figure 5.5a) or shoot extension (Figure 5.5b). In contrast, the relationship between $Ar_{(BH)}$ and TGR was the only growth response to carry significance ($p < 0.02$) in *A. negundo.* Although the significance of these relationships varied, the slopes for all growth responses for each species carried negative values, illustrating the negative effects of increasing root removal on above-ground growth. Both species reduced the surface area of new leaves compared to controls, in order to reduce net water loss in response to the root severance. The proportional odds model (Figure 5.5d) was significant for *A. negundo.*

Increasing $Ar_{(BH)}$ led to premature leaf shedding in both species (Figure 5.5d) and increased visual symptoms of stress. For the practitioner, this type of response is the easiest to comprehend in a relatively short time frame following root removal. The competition factor positively influenced the shoot extension of *A. palmatum*, presumably through phototropic growth in response to an increasing number of neighbouring trees. No other growth responses were affected by the competition factor.

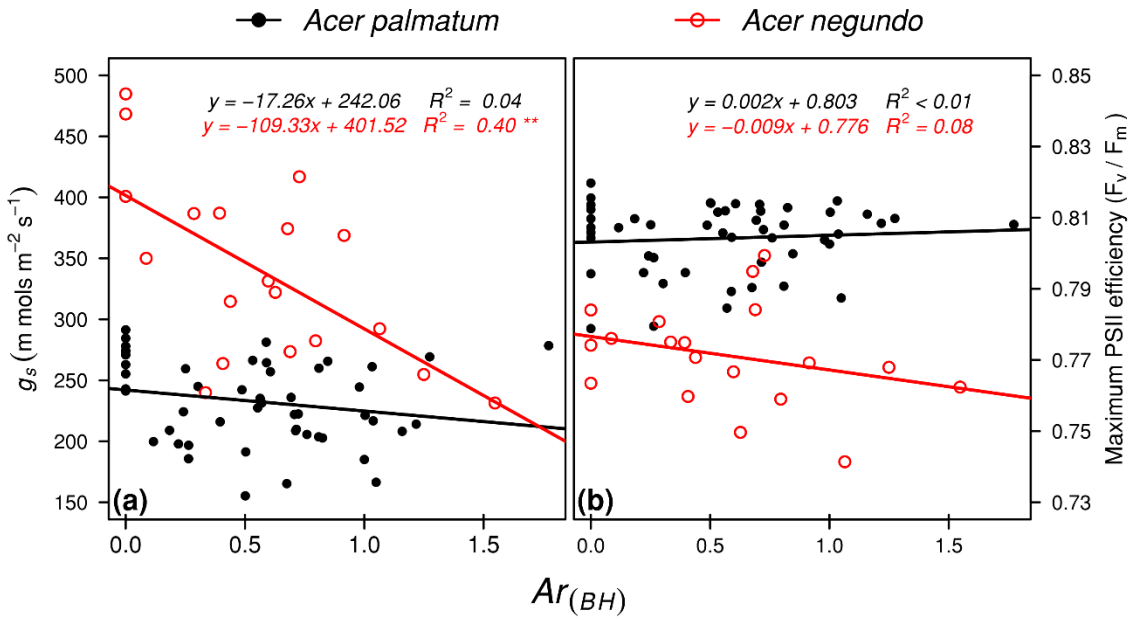

Figure 5.4: Scatterplots and regression lines for seasonal mean stomatal conductance (g_s) in m mol m^{-2} s^{-1} (a) and maximum photosystem II photochemical efficiency (Fv/Fm) (b) responses using $Ar_{(BH)}$ as the explanatory variable.

Table 5.6: Regression statistics for linear models using $Ar_{(BH)}$ to explain differences in trunk area growth rate (TGR) (ln($cm^2 day^{-1}$), shoot extension (mm) and leaf area (cm^2). Significance codes. * $p \leq 0.05$ ** $p \leq 0.01$ *** $p \leq 0.001$

Species	Statistic	Response		
		TGR (ln(cm^2 day^{-1}))	Shoot extension (mm)	Leaf area (cm^2)
Acer palmatum 'Bloodgood'	R^2	<0.01	0.03	0.16
	Model significance	n.s	n.s	***
Acer negundo	R^2	0.31	0.08	0.17
	Model significance	*	n.s	n.s

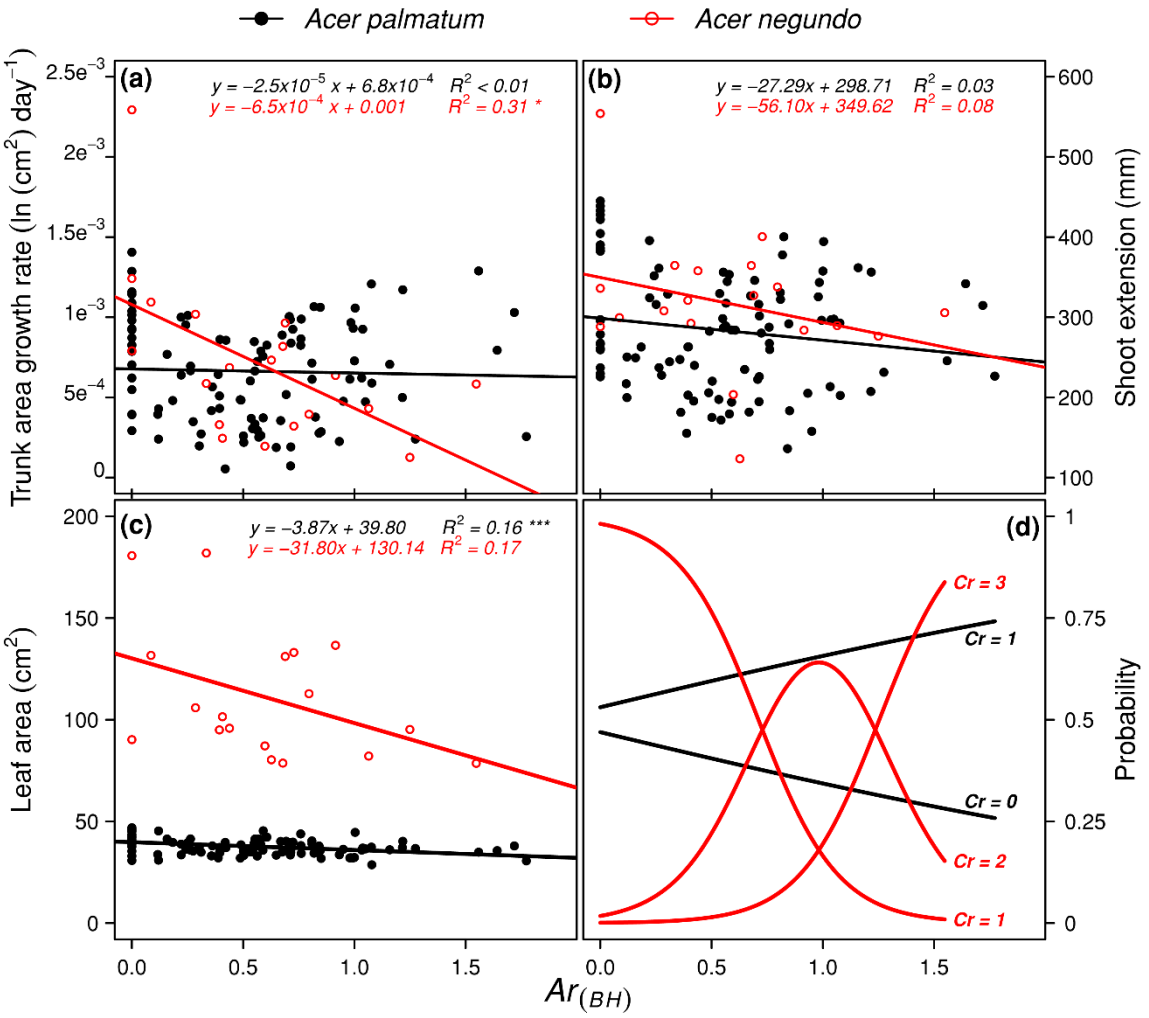

Figure 5.5: Scatterplots and regression lines for trunk area growth rate (TGR) at 1.4 m (ln(cm^2 day-1)) (a); shoot growth (mm) (b); leaf area (cm^2) (c); and the proportional likelihood model for condition rating (*Cr*) (probabilistic scale 0 - 1) (d) using $Ar_{(BH)}$ as the explanatory variable. *Cr*:- 0 = 0% dieback. 1 = 1%-25% dieback. 2 = 26%-50% dieback. 3 = 51%-75% dieback. 4 = 76%-99% dieback. 5 = 100% dieback

5.5 Study limitations

This study was limited by the numbers of mature trees available for destructive root manipulation. It was fortuitous to have been able to secure trees donated by a commercial nursery (Site 1) and local government authority (Site 2). The nursery proprietor has since ceased production of this variety of *Acer,* and in July 2017 the trees were felled. Whilst it would have been desirable to monitor the responses of these trees in subsequent growing seasons, this was unfortunately not an option which was available, and so the study was carried out over just one growing season.

In this first look at hypothesis testing using allometric relationships between root and trunk areas, it would seem that the root removal treatments, to which these two species of *Acer* were exposed, may have been insufficient to induce severe water stress. It is noted, however, that the growing season in which the study was undertaken, was the wettest since the trees were planted in their respective locations, and thus water availability to the remaining portions of the root systems was unlikely to be a contributor to the water stress response. In the absence of ground water recharge following the root removal, it could be expected that more severe physiological stress symptoms would occur (Dong et al., 2016).

Whilst several of the continuous response relationships were significant, the $Ar_{(BH)}$ variable often explained very little of the variance (R^2 values) in the subtle changes in g_s and Fv/Fm in this study. This is likely due to the absence of a sufficient stress response as previously outlined. Furthermore, the physiological responses varied with time throughout the experiment, which may be due to the previously described late-season precipitation in combination with newly forming roots. The $Ar_{(BH)}$ values used in the analyses remained constant throughout the experiment. While not measured, incremental trunk diameter growth and newly growing roots would have resulted in microvariations in the $Ar_{(BH)}$ ratios over time. The practicalities and potential for the introduction of sources of error preclude repeated excavations to measure newly formed roots.

However, ongoing trunk diameter measurements gathered at the same time as the physiology data, may help to account for the subtle differences in the $Ar_{(x)}$ ratios in future studies using this method. The treatment effects, however, were able to detect significant differences in stomatal conductance for each species. It is possible that other hydrological response variables may be more sensitive to $Ar_{(BH)}$. For example, pre-dawn leaf water potential is a highly sensitive measure of plant water status (Améglio et al., 1999) and sap-flow is a key indicator of plant hydraulic functioning (Steppe et al., 2015). The use of one or both of these techniques should be considered for any future work using the $Ar_{(x)}$ parameter, as well as longer-term investigations to test the robustness and longevity of the relationships.

5.6 Conclusions

The results show that root pruning negatively affects the growth and physiology of *A. palmatum* 'Bloodgood' and *A. negundo* in New Zealand. The results concur with the work of Fini et al (2013b), in that root severance indirectly leads to water stress, which is a major limiting factor for tree growth in a range of species (Leuschner et al., 2001; Fini et al., 2009; Martinez et al., 2013a; Weemstra et al., 2013; Marqués et al., 2016). Root pruning negatively affected leaf gas exchange in both species, characterised by reduced stomatal conductance. In the short term, and following a period of ground water recharge, *A. palmatum* 'Bloodgood' and *A. negundo* trees exposed to minor, (T1, T2), or even moderate (T3) root pruning treatments, were able to bring physiological processes back to expected norms following a period of stress.

The results show that there are significant relationships between $Ar_{(x)}$ and $As_{(x)}$ and the physiological and morphological responses to root severance, although model strength varied. There was no discernible difference between $Ar_{(x)}$ and $As_{(x)}$ ratios in terms of their explanatory capabilities. It is possible that, for larger trees with greater heartwood areas, that the $As_{(x)}$ variable may improve model accuracy.

One of the objectives of this research was to investigate whether allometric modelling could be used to derive a root pruning threshold; below which the negative effects of root severance could be avoided. No curvature in the response data was observed, which precluded locating an inflection point; or finding the steepest part of a slope where changes in the response variable were greatest.

Significant reductions in above-ground growth were observed beginning in the T1 and T2 treatments for *A palmatum* 'Bloodgood' (shoot extension and leaf area) and *A. negundo* (TGR) respectively. Mean $Ar_{(BH)}$ values and respective 95% confidence intervals (in parentheses) were 0.32 (0.22;0.41) and 0.55 (0.27;0.83) for T1 and T2 treatments in *A. palmatum* and *A. negundo* respectively. It is concluded then, that when the total combined cross-sectional area of severed roots exceeds 22% and 27% of the trunk cross-sectional area at 1.4 m ($Ar_{(BH)}$ = 0.22 and 0.27) for *A palmatum* 'Bloodgood' and *A. negundo* trees (respectively) in New Zealand, there is potential for significant reductions in above-ground growth when compared to controls. In addition, a sustained reduction in stomatal conductance in the T4 treatment for *A palmatum* 'Bloodgood' was observed, when the mean $Ar_{(BH)}$ value and respective 95% confidence intervals (in parentheses) was 0.83 (0.69;0.97). These physiological stress symptoms have the potential to appear when the total combined cross-sectional area of severed roots exceeds 69% of the trunk cross-sectional area at 1.4 m for *A palmatum* 'Bloodgood'.

Further work is needed to investigate the suitability of the allometric relationship between trunk and root areas and its potential application as a practical tool in the modern arboricultural practitioner's environment. Testing the model by exposing trees to different treatment types may strengthen understanding and assist with more predictive interpretations. Additionally, testing the theory on a different range of species with differing age classes, and monitoring their response over longer periods, may yield more generalisable information.

5.7 Epilogue

With reference to research question number 1 (What effect will an increasing number of trenches in which roots are severed have on tree growth and physiology?), each species responded differently. For *A. palmatum*, the growth responses were uniformly observed across all treatments, where the conductance response increased in severity with an increasing number of trenches. For *A. negundo*, there was a general trend towards increasing severity of response with increasing number of trenches both for growth and physiology responses.

The main objective of this experiment was to investigate the allometric hypothesis, and to answer research question number 5 (Can the allometric relationship between trunk and root cross-sectional area be used as a tool to quantify a root pruning threshold above which negative effects are avoided?). The absence of curvature in the continuous response relationships, precluded locating an asymptote, or inflection point, which may have otherwise indicated a threshold at which the response to root loss noticeably changed. In the absence of curvature, the confidence intervals for the treatment groups were used to prescribe an $Ar_{(BH)}$ threshold above which significant changes in tree growth could be expected to occur. Those were found to be 0.22 and 0.27 for *A. palmatum* 'Bloodgood' and *A. negundo* respectively. These $Ar_{(BH)}$ values correspond to total severed root cross-sectional areas equating to 22% and 27% of the trunk cross-sectional area at 1.4 m for the same species respectively. If this were to be applied in a practical way, it would not be recommended to sever roots with $Ar_{(BH)}$ values which exceed these values.

The purpose of employing the allometric variable was to account for cumulative root loss. Another way this can be achieved is to sever roots in trenches made not at a fixed distance from the tree base – as this investigation did – but in trenches made at distances defined as multiples of trunk diameter, i.e. relative to the size of the tree.

Chapter 6: Testing tree protection zones

The contents of this chapter have been reproduced from:
Benson, A., Koeser, A. and Morgenroth, J. (2018). A test of tree protection zones: Responses of live oak (Quercus virginiana Mill) trees to root severance treatments. Urban Forestry and Urban Greening. 38, 54-63. 10.1016/j.ufug.2018.10.015

6.1 Preamble

This investigation was undertaken using *Quercus virginiana* in Florida, USA. Although constrained by logistics and tree numbers, suitable trees were located at the Plant Science Research and Education Unit, in Citra. The condition rating applied to the *Acer* in New Zealand was not applied in this study for two reasons.

1. The results would have been confounded by the effects of hurricane Irma, which detached numerous terminal leaves.
2. Up until the arrival of the hurricane, the trees had not exhibited any of the visible signs of root pruning described in the condition rating.

The purpose of this investigation was to answer research questions numbers 2 and 5.

Research question 2: How big does a tree protection zone need to be to avoid the negative effects on tree growth and physiology?

Research question 5: Can the allometric relationship between trunk and root cross-sectional area be used as a tool to quantify a root pruning threshold above which negative effects are avoided?

The materials and methods section in this chapter has been edited from its original form to avoid repetition of the methods previously described in section 3.2, and in Chapter 4.

6.2 Introduction

6.2.1 Tree root structure and function

The root systems of woody plants consist of a framework of woody perennial roots, and a vast network of short-lived fine roots (Pallardy, 2008). Roots may spread laterally, well beyond the canopy line of decurrent broadleaf trees (Gilman, 1989; Day et al., 2010). For excurrent trees, such as various gymnosperms and conifers, roots may spread laterally for distances up to three quarters of the height of the tree (Strong and La Roi, 1983), or more depending on soil characteristics (Rigg and Harrar, 1931).

Fine roots absorb and transport water and minerals, and thus play important roles in photosynthesis and tree growth (Hamilton, 1988; Day et al., 2010). Large woody tissues at the tree base act as storage organs for carbohydrates (Hay and Woods, 1978; Coutts, 1987). In deciduous trees particularly, the resources contained in the woody tissues are essential for vigorous spring growth, enabling trees to meet the energy needs required for bud break and initial shoot growth and leaf expansion, when photosynthate production is low (Priestley, 1963; Hansen, 1967, 1971).

Severing roots places constraints on a tree's ability to uptake water and minerals (Jim, 2003), inducing physiological and morphological stress. Morphological responses to root severance include reduced growth (Khan et al., 1998; Ferree et al., 1999; Wajja-Musukwe et al., 2008; Pretzsch et al., 2016), general reductions in overall vitality, premature leaf shedding and canopy dieback (Watson, 1998; Benson et al., 2019b). Physiological responses include curtailment of leaf-level carbon gains, photo-oxidative damage, reduced photosynthesis, and reduced transpiration due to closure of stomatal apertures (Fini et al., 2013b; Wang et al., 2014; Dong et al., 2016; Benson et al., 2019b). An adequate supply of stored carbohydrates can enable trees to retain vigour and recover from such injuries (Hamilton, 1988). It is therefore critical for arboricultural practitioners to understand the implications of root removal, if they are to make informed tree management decisions.

Whilst trees offer a broad range of ecosystem services (Salmond et al., 2016; Wang and Akbari, 2016; Reed et al., 2017; Richards and Edwards, 2017; Riley et al., 2018; Scholz et al., 2018), they are frequently exposed to external pressures through construction work and development (Sandfort and Runchk III, 1986; Vander Weit and Miller, 1986; British Standards Institute, 2012). Trees growing in the urban environment may be subject to root loss during a variety of activities, due to conflicts with built infrastructure (Baines, 1994; Thomson and Rumsey, 1997; Čermák et al., 2000; Randrup et al., 2001; Jim, 2003; North et al., 2017). Adequately catering for the protection of trees is key to promoting their longevity, and the values and benefits which they provide (Despot and Gerhold, 2003; Vogt et al., 2015).

6.2.2 Tree protection methods: A brief review

There exists around the globe a suite of guidelines, best management practice documents (BMPs) and legislations intended to provide procedures and protocols to afford the necessary protection to urban trees; particularly during greenfield-type developments on undisturbed or unmodified sites. An underpinning component of these documents is the provision of a tree protection zone (TPZ). Tree protection zones are most frequently circular areas around a tree set aside for their preservation, containing enough soil and root volume to sustain tree health and stability. The TPZ is often calculated using a tree's stem diameter at breast height (≈1.4 m) and multiplying it by a certain factor to define the radius of the TPZ. Typically, the tree protection radius equates to 12 times the trunk diameter at breast height (Coder, 1996; Standards Australia, 2009; NZArb, 2011; British Standards Institute, 2012), but may vary depending on tree age and species (Harris et al., 2004). It may also be derived using the farthest lateral branch spread or tree height (Auckland Council, 2018), or a combination of all approaches (The Government of the Hong Kong Special Administrative Region, 2015; Fite and Smiley, 2016). Occasionally, the BMPs make provisions for a structural root zone (SRZ) (a circular area around the trunk containing the tree's structural root plate) (Coder, 1996; Standards Australia, 2009) or make specific recommendations for root pruning thresholds (Standards Australia, 2009; British Standards Institute, 2012; Fite and Smiley, 2016). Table 6.1 summarises a selection of best management practice documents from various geographical locations.

6.2.3 Root system architecture, tree protection zones and tree allometry

The BMPs rely on an established relationship between trunk diameter and root system architecture to enable arboricultural practitioners to easily derive the various tree protection zones, or synonyms thereof. Trunk diameter is an excellent predictor of root (Day et al., 2010) and crown (Peper et al., 2001) spread. Correlations have long been established between trunk diameter and lateral root spread for a range of broadleaf species (Tubbs, 1977; Gilman, 1989; Gerhold and Johnson, 2003). Whilst there is mention in the aforementioned BMPs of the use of the canopy spread or height methods of defining a tree protection zone, in a meta-analysis, Day et al. (2010) established that these relationships were not accurate predictors of root system spread (canopy diameter, no relationship; tree height, $R^2 = 0.36$). In contrast, it was shown that trunk diameter at 1.4 m (DBH) accurately accounted for 89% of the variability (calculated as R^2) in lateral root spread in urban trees, with trunk diameters up to ≈ 70 cm.

Despite the similarities between the BMPs, the principles of the tree protection zone have not been extensively tested (Watson, 1998), and research is needed to determine specific root care practices (Costello et al., 2017). The objectives of this study were to test the suitability of a range of tree protection zones by monitoring the responses of mature trees to different root removal treatments over the course of a growing season. Additionally, the study builds on the work in Chapter 5 (Benson et al., 2019b) and further investigates the suitability of allometric relationships between trunk and root cross-sectional areas as a tool to quantify root pruning treatments. Cross-sectional area relationships of this nature may stem from the Pipe Model Theory of Tree Form (Shinozaki et al., 1964a, b), which describes the relationship between the conductive sapwood area in the trunk, and other tissues such as leaves (Shinozaki et al., 1964a; Vertessy et al., 1995; Grabosky et al., 2007; Lubczynski et al., 2017b) and root systems (Shinozaki et al., 1964b; Kaipiainen and Hari, 1985; Gould and Harrington, 2008).

Table 6.1: Summary of various best management practice documents

Text	Country of origin	Author	TPZ (or equivalent) radius	Structural root zone (SRZ) (or equivalent) radius	TPZ encroachment threshold	Root diameter threshold
BS5837:2012 Trees in Relation to design, demolition and construction: Recommendations.	United Kingdom	British Standards Institute (2012)	Referred to as a "Root protection area" (RPA). 12 times trunk diameter at 1.50 m.	Not defined.	New impermeable surfaces should affect no more than 20% of the permeable RPA	25 mm.
Arboriculture: integrated management of landscape trees, shrubs, and vines (USA).	USA	Harris et al. (2004)	6 to 18 times trunk diameter at 1.40 m metres depending on species and age.	Not defined.	None	Not defined.
Best Management Practices (BMP) - Managing Trees During Construction.	USA	Fite and Smiley (2016)	Drip line method or 6 to 18 times trunk diameter at 1.40 m depending on species and age. Discretion is awarded to the arborist who needn't be constrained by the quantitative methods provided.	Defined as "the area immediately adjacent to the trunk where roots essential for tree health and stability are located."	None specified. Recommendation to avoid encroachment or offset the encroachment area with a contiguous area of ground.	Roots ≥25 mm should be cut with a saw or loppers and not left damaged by excavation equipment.
National Joint Utilities Group (NJUG) Guidelines for the planning, installation and maintenance of utility apparatus in proximity to trees.	United Kingdom	National Joint Utilities Group (2007)	4 times the trunk circumference.	A circular area around the trunk with a radius of 1 metre from tree base.	Not defined. Methods to exclude heavy machinery.	25 mm.
A guideline for tree and bush protection on development sites.	New Zealand	NZArb (2011)	4 times the trunk circumference.	A circular area around the trunk with a radius of 1 metre from tree base.	None.	Not defined.
AS 4970-2009 Protection of Trees on Development Sites.	Australia	Standards Australia (2009)	12 times trunk diameter at 1.40 m.	$SRZ_{(m)}$ = (Trunk diameter at ground level x 50)$^{0.42}$ x 0.64.	10% providing the area can be offset with a contiguous area elsewhere.	Not defined.
Guidelines on Tree Preservation during Development.	Hong Kong	The Government of the Hong Kong Special Administrative Region (2015)	Drip line, tree height or between 6 and 18 times the trunk diameter at 1.40 m.	Not defined.	None, without "special approval".	Not defined.
Construction Damage Assessments: Trees and Sites.	USA	Coder (1996)	1.25 feet of radius for every 1 inch of trunk diameter (15 times trunk diameter).	Tabulated data plotted to give; $SRZ_{(m)}$ = (0.27 x $DBH_{(cm)}^{0.56}$)	None.	Not defined.

6.3 Materials and methods

6.3.1 Study sites and trees

The study was conducted on 18 cathedral live oak (*Quercus virginiana* Mill 'SDLN') (mean trunk diameter at 1 m = 28.25 cm, δ = 7.36 cm) planted from 170 L containers into a loamy sand (mean bulk density = 1.53 g/cm^3 (δ = 0.07 g/cm^3, n = 5)) at the University of Florida's Plant Science Research and Education Unit in Citra, Florida, USA (29° 24' 37.19" N. 82° 09' 57.96" W). Trees were planted in July 2006 into three rows with 15 m spacing between trunk centres. Mean annual rainfall for the study site is 1,210.56 mm and mean annual temperature is 20.58 °C (FAWN, N.D). Temperature and rainfall were recorded using an on-site weather station with data loggers (Campbell Scientific, Logan, Utah, USA) (Figure 6.1). In the latter stages of the study, the site and surrounding area were affected by Hurricane Irma (Cangialosi, 2018). Though all trees remained standing following the hurricane, they were subjected to acute low temperatures, high precipitation and sustained winds exceeding 60 km/h.

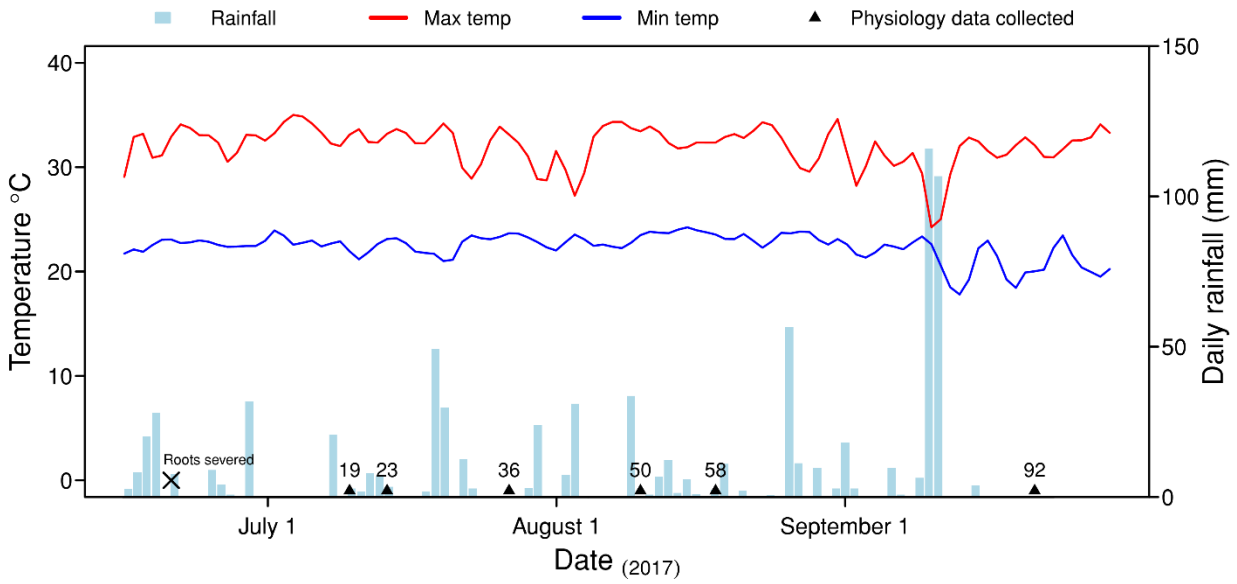

Figure 6.1: Meteorological conditions throughout the experimental period. Triangles denote days on which physiological data were gathered with corresponding numbering denoting the number of days following root severance.

6.3.2 Root pruning treatments

Trees were randomly allocated to one of six treatment groups with three replicates of each treatment. Treatments were prescribed based on trunk diameter at 1 m, since only 2 of the 18 trees had trunks that were free of scaffold branching or occluded pruning cuts at 1.40 m. Root pruning treatments consisted of a circular trench around the base of each tree (except control) with a radius defined by its trunk diameter at 1 m. Treatments ranged from 3 to 15 times the trunk diameter in increments of three (3x, 6x, 9x, 12x and15x) plus control.

Between the 19th and 22nd June 2017, trenches ≈ 500 mm deep and ≈ 100 mm wide were excavated using pneumatic soil displacement (Air Spade, Guardair, Chicopee, MA, USA). Roots spanning the trenches were severed manually during the same period using either loppers or a hand saw, and fragments of each root were completely excised before filling in the trenches with the original soil material.

Following root removal, root cross-sectional area ratios for whole trunk area were determined using Equations 3.1 to 3.3 inclusive. After first estimating the trunk conductive sapwood area of each tree at 1 m following the method described in Chapter 4, and applying the correction for *Q. virginiana* (Table 4.2), root cross-sectional area ratios were then expressed as a proportion of the trunk conductive sapwood area at 1 m using Equation 3.4. Precipitation totalling 173.74 mm fell over eleven of the 14 days prior to the ERT being undertaken. It is therefore possible that the sapwood areas may have been marginally overestimated.

6.3.3 Tree responses to root pruning

6.3.3.1 Tree responses to root pruning – Physiology

Pre-dawn leaf water potential (Ψ), stomatal conductance (g_s), chlorophyll fluorescence variables and volumetric soil moisture (θ) were measured periodically (approximately every 10 to 14 days, pending favourable meteorological conditions) throughout the experimental period (June to September 2017 inclusive). Pre-dawn leaf water potential was measured between 03:00 a.m. and 05:00 a.m. using a pressure chamber (PMS Instruments, Albany, Oregon, USA) from two fully expanded leaves at the second node proximal to the terminus of an equivalent number of new twigs from each tree. Stomatal conductance measurements were made using an SC-1 leaf porometer (Meter Environment, Washington, USA) calibrated to local conditions using the SC-1 Leaf Porometer Calibration Kit (part# 30425, Meter Environment, Washington, USA). Dark-adapted chlorophyll fluorescence variables were measured using an OS30P+ (Optisciences, Hudson, New Hampshire, USA).

Conductance and fluorescence data were gathered from three fully expanded sun leaves at the second node proximal to the terminus of an equivalent number of new twigs between 08:30 and 11:00. The dark-adaptation period was 30 minutes. Fluorescence data are absent on the second data gathering exercise (23 days after root severance) due to a device malfunction. Volumetric soil moisture data (θ) were recorded during sunrise (06:30 a.m. – 07:30 a.m.) at two locations per tree using a handheld data-logger (Pro-Check, Meter Environment, Washington, USA) equipped with a soil moisture probe (GS3, Meter Environment, Washington, USA).

6.3.3.2 Tree responses to root pruning – Tree growth

Trunk diameters at ground level, 500 mm and at 1 m were recorded immediately prior to root severance treatments and again at the end of the experimental period (21st September). Shoot growth was measured using 18 new terminal shoots per tree and leaf area was measured from ten sun leaves harvested from the third node proximal to the terminus of an equivalent number of twigs from each tree using an LI-3100C leaf area meter (LI-COR Devices, Nebraska, USA).

6.3.4 Statistical analyses

All data were analysed using R statistical software version 3.4.4 (R Core Team, 2018). One-way ANOVA were employed to test for significant differences in response to the root pruning treatments. Post-hoc Dunnett's tests were used for comparisons of significance between treatments and control. Linear regression models were fitted to physiological (Ψ, g_s, Fv/Fm and Fo) and morphological (trunk diameter growth, new shoot extension and leaf area) response data using root cross-sectional area ratios ($Ar_{(1)}$ and $As_{(1)}$) as the explanatory variables with the lm() function. Soil moisture data were introduced into the analytical models as a covariate for physiological responses. Normally distributed residuals for each relationship between treatment and response were checked and confirmed by examining the quantile-quantile plots using the plot() function. Unless otherwise indicated, all tests for significance are reported at $p \leq 0.05$.

6.4 Results and discussion

6.4.1 Sapwood areas

The tomographic analyses revealed that all trees had distinct heartwood and sapwood regions, characterised by a central region of high resistivity (as seen in Figure 4.1) and the corresponding Gaussian resistivity profiles (as seen in Figure 4.5). Noting that the ERT may have marginally overestimated the sapwood area due to precipitation events, sapwood areas ranged from 266.70 cm^2 to 796.06 cm^2, corresponding to 59% to 71% of the total trunk cross-sectional area. Thus, the $As_{(1)}$ variable is distinct from the $Ar_{(1)}$ variable.

6.4.2 Root cross-sectional area ratios

Root cross-sectional area ratios ($Ar_{(1)}$ and $As_{(1)}$) increased as the proximity of the treatment to the tree base increased (15x to 3x) ($p < 0.0001$). Across all treatments, total severed root cross-sectional areas were between 0.08 and 0.52 times the trunk cross-sectional area at 1 m ($Ar_{(1)}$), and 0.16 and 1.03 times the trunk conductive sapwood area at the same height ($As_{(1)}$). Mean values for $Ar_{(1)}$ and $As_{(1)}$ ratios plus or minus one standard error (in parentheses) are presented in Table 6.2. The relationship between total severed root cross-sectional area and treatment is seen in Figure 6.2.

Table 6.2: Mean $Ar_{(1)}$ and $As_{(1)}$ ratios for each root pruning treatment ± one standard error (in parentheses). Different letters in a single column denote a significant difference between treatments.

Treatment	***Ar*$_{(1)}$**	***As*$_{(1)}$**
15x	0.08 (0.01) a	0.17 (0.02) a
12x	0.16 (0.04) a	0.59 (0.21) ab
9x	0.21 (0.06) a	0.43 (0.13) ab
6x	0.20 (0.03) a	0.38 (0.06) a
3x	0.52 (0.06) b	1.03 (0.16) b

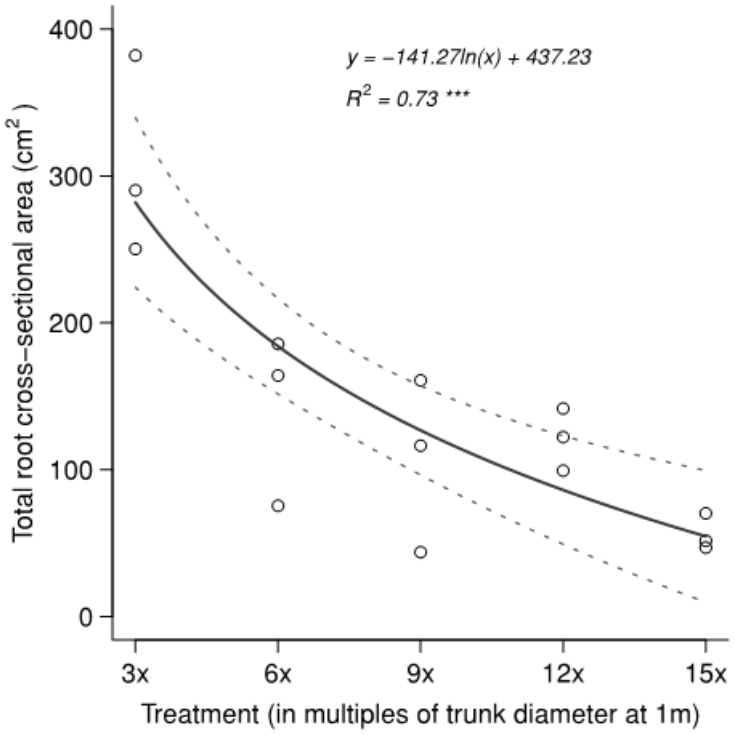

Figure 6.2: Relationship between the distance of the circumferential trench from the tree base (treatment) and total root cross-sectional area severed. Dashed lines denote 95% confidence intervals.

6.4.3 Physiological responses to root pruning

6.4.3.1 Physiological responses of trees to root severance treatments

Pre-dawn leaf water potential was negatively affected by treatment ($p < 0.01$) on all but the first of the measuring days (day 19) following root severance (Figure 6.3, Table 6.3). On day 23, significant differences between the control and the 3x, 6x and 9x treatments were observed. By day 50, all treatments except 15x were significantly different from the controls; observed again on day 58. By day 92, the 12x treatment appeared to show signs of recovery and only the 3x, 6x and 9x treatments exhibited differences between the control. No effect of the volumetric soil moisture on the Ψ response was observed, and thus it is posited that the apparent recovery of the 12x treatment on day 92, was due to a sufficient number of newly grown roots contributing to hydrological demands.

Pre-dawn leaf water potential is a highly sensitive and widely available measure of plant water status. (Améglio et al., 1999). The negative effects observed in the Ψ response of the root pruned trees are consistent with the responses of other species subjected to root pruning (Fini et al., 2013b; Wang et al., 2014; Dong et al., 2016) and water stress (Epron et al., 1992; Kubiske et al., 1996; Zwack et al., 1998; Fini et al., 2013a), including *Q. virginiana* (Cavender-Bares et al., 2007).

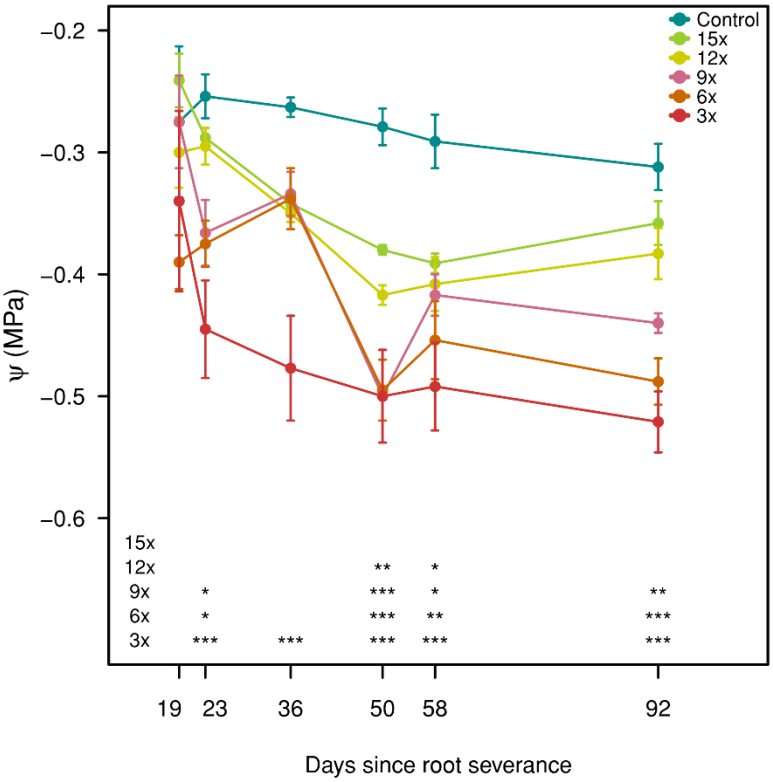

Figure 6.3: Treatment mean pre-dawn leaf water potential (Ψ) in MPa plotted against number of days since roots were severed. Error bars show ± one standard error (SE). Asterisks in the inset matrix show significant differences between control and treatment (left hand side) on a particular day with the following significance codes; * $p \leq 0.05$ ** $p \leq 0.01$ *** $p \leq 0.001$

Conductance and fluorescence responses were not significantly affected by the treatment, although the volumetric soil moisture had intermittent effects (Table 6.3). *Q. virginiana* exhibited anisohydric behaviour (Beeson, 2014) in response to the root severance treatments. The stomatal apertures of anisohydric plants can remain open for longer, concomitantly sustaining high photosynthetic rates for extended periods, even in the presence of decreasing leaf water potential (Sade et al., 2012).

Additionally, *Q. virginiana* is a sclerophyllous species (Monk, 1987), adding rigidity to the leaves. The presence of sclerophyll in the leaves better allows plants to resist reducing leaf turgor (Oertli, 1989; Oertli et al., 1990) and maintain stomatal openings (Lo-Gullo and Salleo, 1988; Pigott and Pigott, 1993), a trait observed in other sclerophyllous *Quercus* species (Salleo and Lo-Gullo, 1990).

Table 6.3: Treatment effect results of ANOVA significance tests for predawn leaf water potential (Ψ (MPa)), stomatal conductance (g_s) (m mol m^{-2} s^{-1}), minimum PSII chlorophyll fluorescence signal (Fo) and maximum PSII photochemical efficiency (Fv/Fm) responses. The effect of volumetric soil moisture (θ (%)) on each response is also included. Significance codes. * $p \leq 0.05$ ** $p \leq 0.01$ *** $p \leq 0.001$

Response	**Effect**	**Days since root severance**					
		19	**23**	**36**	**50**	**58**	**92**
Ψ	Effect of treatment	n.s	***	***	***	**	***
	Effect of θ	n.s	n.s	n.s	n.s	n.s	n.s
	Effect of treatment x θ	n.s	n.s	n.s	n.s	n.s	n.s
g_s	Effect of treatment	n.s	n.s	n.s	n.s	n.s	n.s
	Effect of θ	*	n.s	*	n.s	n.s	n.s
	Effect of treatment x θ	n.s	n.s	n.s	n.s	n.s	n.s
Fo	Effect of treatment	n.s	-	n.s	n.s	n.s	n.s
	Effect of θ	*	-	n.s	n.s	n.s	n.s
	Effect of treatment x θ	*	-	n.s	n.s	n.s	n.s
Fv/Fm	Effect of treatment	n.s	-	n.s	n.s	n.s	n.s
	Effect of θ	*	-	**	n.s	n.s	n.s
	Effect of treatment x θ	n.s	-	*	n.s	n.s	n.s

6.4.3.2 Physiological responses of trees using severed root cross-sectional area ratios

Figure 6.4 depicts mean physiological responses using $Ar_{(1)}$ and $As_{(1)}$ as the explanatory variables. Mean data were established using the arithmetic mean of all physiology data for each response gathered for each tree throughout the study. Regression statistics for linear models on each measuring day, as well as the mean, are presented in Table 6.4. Of the models shown in Figure 6.4, only the relationship between Ψ and the explanatory variables was significant. Model significance for Ψ was $p < 0.001$ on all but the first measuring day. Significant models were observed for the Fv/Fm response in the early stages of the study (day 19), but only when the θ had an effect. The absence of significant models for g_s and fluorescence responses in *Q. virginiana*, is attributed to the previously described anisohydric behaviour. The work in Chapter 5 involving two different species of *Acer* revealed significant relationships between g_s and Fv/Fm responses using root cross-sectional area ratios ($Ar_{(BH)}$) (Benson et al., 2019b), illustrating the highly dynamic and species-specific nature of tree physiology. Although the regression models for $Ar_{(1)}$ and $As_{(1)}$ were not significant in this study, it is noted that the regression lines are negatively weighted for g_s and Fv/Fm, and positively weighted for Fo, illustrating the negative physiological effects of the root removal.

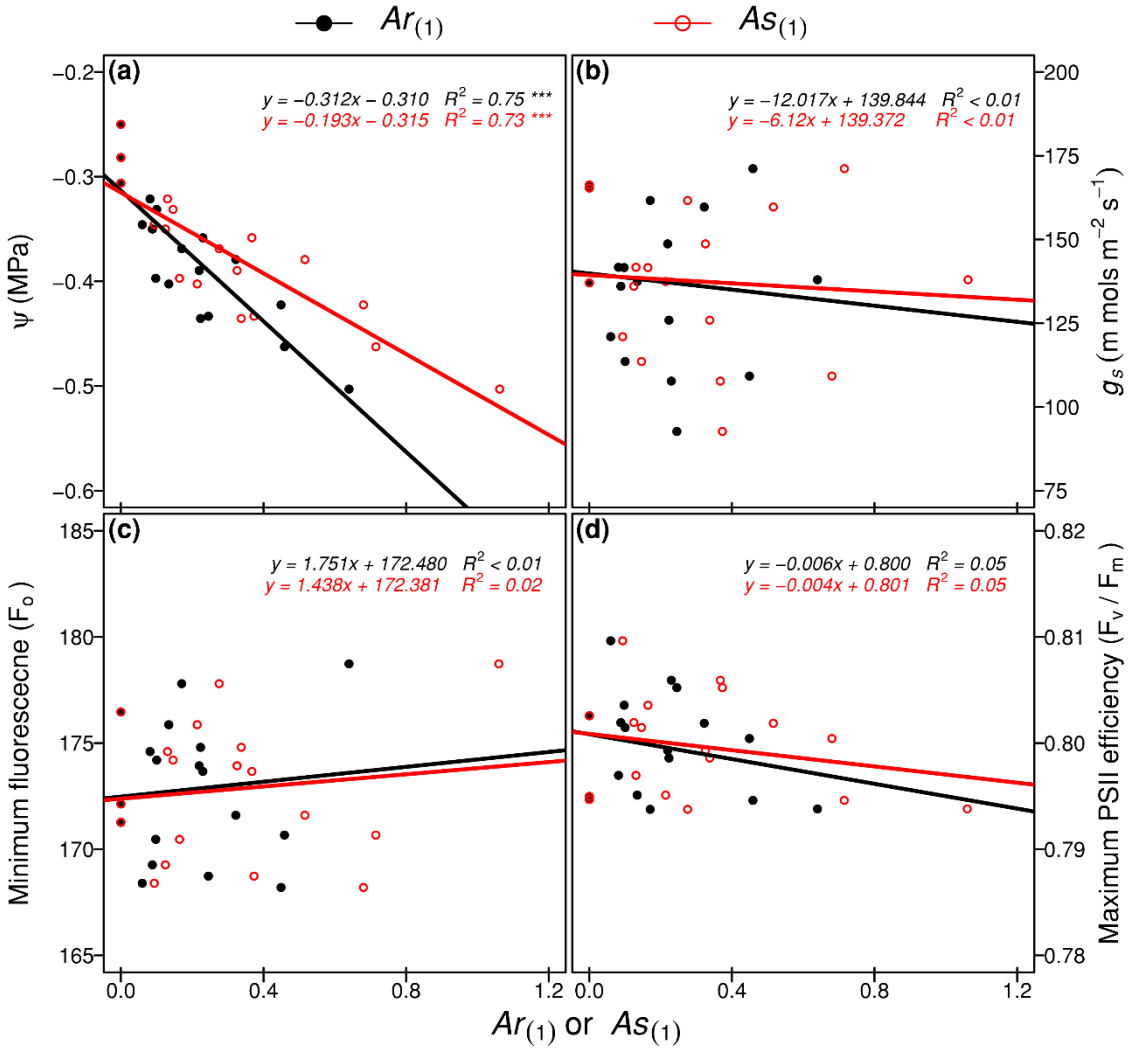

Figure 6.4: Scatterplots and regression lines for mean pre-dawn leaf water potential (Ψ) in MPa (a); stomatal conductance (g_s) in m mol m^{-2} s^{-1} (b); minimum fluorescence signal (Fo) (c); and maximum photosystem II photochemical efficiency (Fv/Fm) (d) responses using $Ar_{(1)}$ and $As_{(1)}$ as the explanatory variables.

Table 6.4: Regression statistics for linear models using $Ar_{(1)}$ and $As_{(1)}$ (in parentheses) to explain differences in pre-dawn leaf water potential (Ψ (MPa)), stomatal conductance (g_s) (m mol m^{-2} s^{-1}), minimum PSII chlorophyll fluorescence signal (Fo) and maximum PSII photochemical efficiency (Fv/Fm) responses. The effect of volumetric soil moisture (θ (%)) on each response is also included. Where no parentheses are shown, values for each model are the same. Significance codes. * $p \leq 0.05$ ** $p \leq 0.01$ *** $p \leq 0.001$

Response	Statistic	Days since root severance						
		19	**23**	**36**	**50**	**58**	**92**	**Mean**
Ψ	R^2	0	0.65 (0.66)	0.71 (0.68)	0.54	0.51 (0.49)	0.68 (0.67)	0.75 (0.73)
	Model significance	n.s	***	***	***	*** (**)	***	***
	Effect of θ	n.s	n.s	n.s	n.s	n.s	n.s	n.s
	Effect of interaction	n.s	n.s	n.s	n.s	n.s	n.s	n.s
gs	R^2	0.02	<0.01	0.23	0.01	0.05	<0.01	<0.01
	Model significance	n.s	n.s	n.s	n.s	n.s	n.s	n.s
	Effect of θ	n.s	n.s	*	n.s	n.s	n.s	n.s
	Effect of interaction	n.s	n.s	n.s	n.s	n.s	n.s	n.s
Fo	R^2	0.01 (0.14)	-	0.04	0.23 (0.22)	0.01 (0.02)	0.01 (<0.01)	<0.01 (0.01)
	Model significance	n.s	-	n.s	n.s	n.s	n.s	n.s
	Effect of θ	n.s	-	n.s	*	n.s	n.s	n.s
	Effect of interaction	n.s	-	n.s	*	n.s	n.s	n.s
Fv/Fm	R^2	0.34 (0.35)	-	<0.01	<0.01	<0.01	0.12 (0.11)	0.05
	Model significance	*	-	n.s	n.s	n.s	n.s	n.s
	Effect of θ	*	-	n.s	n.s	n.s	n.s	n.s
	Effect of interaction	n.s	-	n.s	n.s	n.s	n.s	n.s

6.4.4 Tree growth response to root pruning

6.4.4.1 Growth responses of trees to root severance treatments

The above-ground growth of *Q. virginiana* was negatively affected by the root pruning treatments (Figure 6.5). Trunk growth was significantly affected in the 3x treatment (mean $Ar_{(1)}$ = 0.52) 92 days after the root pruning (Figure 6.5a). New shoot extension was negatively affected by treatment, and significant differences between treated trees and control emerged at the 9x treatment (mean $Ar_{(1)}$ = 0.21) (Figure 6.5b). Leaf area was also negatively affected, although differences emerged only at the 3x treatment (mean $Ar_{(1)}$ = 0.52) (Figure 6.5c).

6.4.4.2 Growth responses of trees using severed root cross-sectional area ratios

The relationships between $Ar_{(1)}$ and $As_{(1)}$ and the above-ground growth responses are seen in Figure 6.5d to f; regression statistics for each model are presented in Table 6.5. The relationships between $Ar_{(1)}$ and $As_{(1)}$ and trunk diameter growth were significant at $p < 0.01$ (R^2 = 0.47 ($Ar_{(1)}$) and 0.44 ($As_{(1)}$)). The relationships between $Ar_{(1)}$ and $As_{(1)}$ and new shoot extension (R^2 = 0.58 ($Ar_{(1)}$) and 0.55 ($As_{(1)}$)) and between $Ar_{(1)}$ and $As_{(1)}$ and leaf area (R^2 = 0.57 ($Ar_{(1)}$) and 0.56 ($As_{(1)}$)) were significant at $p < 0.001$. Slope coefficients for each model had negative values, illustrating the negative effects of increasing root removal on above-ground growth.

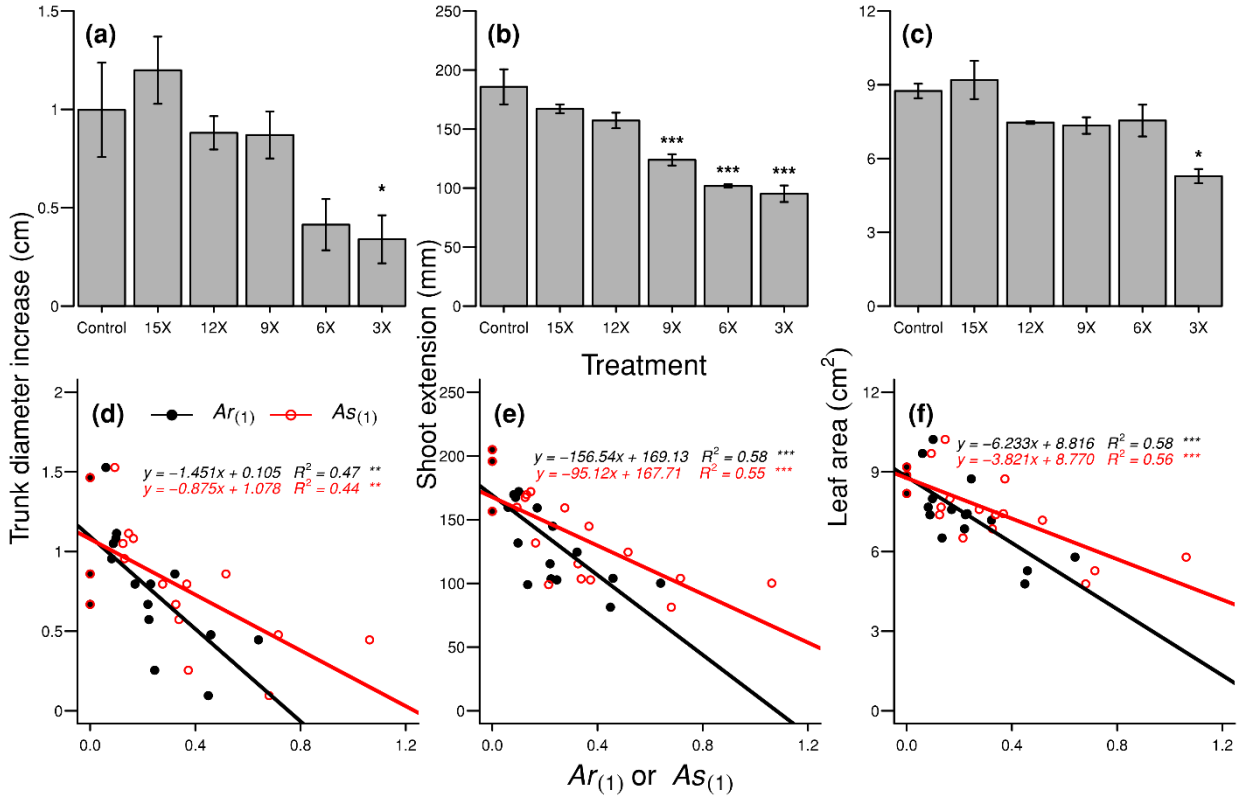

Figure 6.5: Bar plots (upper row) and regression relationships using $Ar_{(1)}$ and $As_{(1)}$ as explanatory variables (lower row) showing growth responses to the root pruning. Error bars on the bar plots show ± one standard error (SE). Asterisks above bars denote significant differences between treatment and control at $p \leq 0.05$ (*), $p \leq 0.01$ (**) or $p \leq 0.001$ (***).

Table 6.5: Regression statistics for linear models using $Ar_{(1)}$ and $As_{(1)}$ (in parentheses) to explain differences in trunk diameter growth (ΔØ (cm)), shoot extension (mm) and leaf area (cm^2). Significance codes. * $p \leq 0.05$ ** $p \leq 0.01$ *** $p \leq 0.001$

Statistic	ΔØ (cm)	Shoot extension (mm)	Leaf area (cm^2)
R^2	0.47 (0.44)	0.58 (0.55)	0.57 (0.56)
Model significance	**	***	***
Slope	-1.45 (-0.87)	-156.54 (-95.12)	-6.23 (-3.82)
Intercept	1.09 (1.08)	169.13 (167.71)	8.82 (8.77)

Although the use of root cross-sectional area ratios ($Ar_{(x)}$ and $As_{(x)}$) is a new concept in root pruning research, significant models for above-ground growth responses have previously been observed using the $Ar_{(x)}$ variable (Benson et al., 2019b). The explanatory power (R^2) and model significance (p value) of the $Ar_{(x)}$ relationships in this study, were greater than those previously observed. One possible reason for this could be that the previous investigation increased the $Ar_{(x)}$ ratio by severing roots on an increasing number of sides of the tree (one (T1) to four (T4) inclusive). Trees in the lesser (T1, T2) or even moderate (T3) treatments would still retain fibrous roots in varying amounts. Since water and soil nutrients are essential for tree growth (Littell et al., 2008; Brzostek et al., 2014), retaining portions of the fibrous root system may have limited the severity of the growth responses in these treatments. In contrast, the circumferential trenches in this study inherently removed all the fibrous roots at the extremity of each tree's root system in all treatments, thereby limiting water and mineral uptake on all sides. Furthermore, the more juvenile trees used in the first study may be more tolerant to root removal (Watson, 1998), because of changes to resource allocation in mature trees (Pryor and Watson, 2016).

Root pruning has been shown to negatively affect the above-ground growth of other species (Watson, 1998; Ferree et al., 1999; Wajja-Musukwe et al., 2008; Fini et al., 2013b; Pretzsch et al., 2016). One possible reason for reduced growth, could be that newly assimilated carbohydrate resources are preferentially allocated to the damaged root systems, in order to respond to the injuries (Rook, 1971; Hamilton, 1988; Amoroso et al., 2010a; Amoroso et al., 2010b) and increase the root to shoot ratio (Sudmeyer et al., 2004; DesRochers and Tremblay, 2009; Dong et al., 2016). Additionally, reducing the surface areas of newly formed leaves may contribute to reducing overall net transpiration and water loss in response to the induced water stress following root removal (Struve and Joly, 1992; Liu and Stützel, 2004; Pallardy, 2008).

This study was limited by the number of available trees, and thus only three replicates for each of the discrete treatment variables. Large numbers of mature trees with a known history are rare for research purposes. As far as is known, this is the first time a root pruning study of this nature has been undertaken on mature trees, and the aim was to test a wide range of tree protection zones with the available resources. The absence of more significant differences between treatments and the growth responses, may be a result of the reduced number of replicates and the associated large standard errors.

Additionally, the study was conducted over the course of just three months. Gathering growth and physiology data over a longer period of time (for example, several years) may reveal temporal recovery of certain treatments (Watson, 1998; Fini et al., 2015), and perhaps more significant differences between treatments, enabling a clearer picture to be formed on the long-term adequacy of different tree protection zones.

Q. virginiana is regarded as a species that is tolerant to both drought (Gilman et al., 2018) and root removal (Matheny and Clark, 1998). Despite this, the negative effects of root severance on growth and physiology over a period of three months were observed. Other species, less tolerant to root removal, may respond more dramatically than live oak, and the findings presented here in relation to required tree protection zone radii may differ by species and age class. The approach taken by Harris et al. (2004) - which accounts for species tolerance to root pruning as well as age class - may be the most suitable method for prescribing tree protection zone radii, although the various distances (as functions of DBH) still require further testing.

To further understand the effects of root removal on mature trees, and specifically research involving root cross-sectional area ratios, exposing trees to a different type of root pruning treatment may reveal more information about how trees respond. Mimicking utility trenching at progressively closer distances to the tree base, may yield information which is more generalisable for urban trees, that are frequently exposed to this kind of ground alteration (Thomson and Rumsey, 1997; Jim, 2003; North et al., 2017).

Additionally, linear excavations of this nature would also mimic trenching works for building foundations, or road edges, such as those typically associated with new housing developments. Using simple algebra, the removed portions of TPZs could be calculated, and current guidelines which prescribe encroachment thresholds for such work could be improved with up-to-date information.

6.5 Conclusions

The results show that root pruning negatively affected the growth and physiology of *Q. virginiana* in Central Florida. Root pruning negatively affected pre-dawn leaf water potential in all but the 15x treatment within 92 days of root removal. Where various BMPs may suggest a 12:1 ratio of trunk diameter be used to prescribe a tree protection zone radius, physiological stress in the 12x treatment was observed 50 days after roots were severed, when the mean $Ar_{(1)}$ ratio was 0.16. It is concluded therefore, that a tree protection zone defined by a radius of 12 times the trunk diameter at 1 metre is insufficient to protect *Q. virginiana* from short-term negative physiological effects of root removal, although is sufficient to avoid sustained water stress symptoms for up to 92 days, as well as negative effects on above-ground growth in the same time period during a summer growing season.

The results would suggest that in order to fully protect trees from the negative effects of root removal associated with development activities, tree protection zones should be prescribed by a radius of 15 times the trunk diameter at 1 metre as a minimum, in line with the Forestry Commission's (UK) guidelines for protecting the root zones of veteran trees (The Forestry Commission and Natural England, 2018) during development.

Significant relationships between $Ar_{(1)}$ and $As_{(1)}$ and pre-dawn leaf water potential and each of the growth responses were observed, although model strength varied. The explanatory power (R^2 value) and model significance (p value) of $As_{(1)}$ were marginally less than that of $Ar_{(1)}$ for each response (physiology and growth), making the ratio of root cross sectional area to trunk cross sectional area ($Ar_{(x)}$), a useful and readily measurable tool for the arboricultural practitioner.

6.6 Epilogue

The main objective of this experiment was to test the principles of the tree protection zone, which to date had not been subjected to empirical scrutiny. This relates to research question number 2 (How big does a tree protection zone need to be to avoid the negative effects on tree growth and physiology?). Within the experimental limitations, it was found that severing roots in circumferential trenches with radii equivalent to 12, 9, 6 and 3 times trunk diameter resulted in short-term water stress symptoms. And that severing roots in circumferential trenches with radii equivalent to 9, 6 and 3 times trunk diameter, resulted in reductions in new shoot extension growth. If this were to be applied in a practical way, it would be recommended that in order to achieve an optimum standard of tree care, and to limit the short-term negative effects of water stress, circular tree protection zones should be prescribed with a radius equivalent to 15 times the trunk diameter at 1 m.

The continuous relationships between $Ar_{(1)}$ and the response variables again exhibited no curvature, and so a threshold at which the response showed the greatest change was not revealed. Unlike Chapter 5, due to the limitations of the experiment (tree numbers), and the way in which increasing $Ar_{(1)}$ was achieved (by making trenches closer to the tree as functions of trunk diameter), the confidence intervals provided no useful information in revealing an $Ar_{(1)}$ value at which root severance should not occur. In this instance, although the continuous relationships were significant, the $Ar_{(1)}$ ratio was of little use to prescribe a threshold.

It was interesting to test the principles of the tree protection zone, and the results may be useful for updating current guidelines. However, perhaps the most common type of root removal which would be encountered in urban trees, would be that involved with linear root cutting, such as during pavement repair or utility trenching.

Chapter 7: Simulating utility trenching

The contents of this chapter have been reproduced from:
Benson, A., Koeser, A. and Morgenroth, J. (2019). The effects of root pruning on mature roadside trees. Urban Forestry & Urban Greening. 46, 126448 10.1016/j.ufug.2019.126448.

7.1 Preamble

This investigation was undertaken using *Quercus virginiana* in Florida, USA, and ran simultaneously to the investigation in Chapter 6. The purpose of this investigation was to replicate as best as possible the typical type of root loss which would occur in an urban environment, e.g. linear root severance due to utility trenching. The condition rating which was applied to the *Acer* in New Zealand was not applied to the trees in this study for the same reasons outlined in Chapter 6.

The purpose of this investigation was to answer research questions numbers 3 and 5.

Research question 3: How close to a tree can roots be severed in a linear trench before sustained stress symptoms are observed?

Research question 5: Can the allometric relationship between trunk and root cross-sectional area be used as a tool to quantify a root pruning threshold above which negative effects are avoided?

The materials and methods section in this chapter has been edited from its original form to avoid repetition of the methods previously described in section 3.2, and in Chapter 4.

7.2 Introduction

City streets are often modified to accommodate an increasing need for utility and network services, due to urban growth and development (Sánchez et al., 2013). Similarly, upgrades to pedestrian and vehicular transport networks are often carried out to meet modern engineering requirements and to accommodate population growth (Chi, 2012; Duranton and Turner, 2012; Chen et al., 2014). Whilst trenchless technologies exist for utility works, their use can be contingent on detailed plans for existing buried infrastructure (Metje et al., 2007), and so many of these types of activities involve trenching works and excavations in the public transport corridor (Rogers et al., 2012). These types of ground alterations can place nearby urban trees at risk of root damage, leading to partial destruction or removal of root systems (Jim, 2003; North et al., 2017) and contributing to increased urban tree mortality (Hauer et al., 1994). Linear excavations which sever roots at distances equating to six times the trunk diameter at breast height (DBH ≈ 1.4 m), may result in the removal of 24.50% of the root system of trees with a 35 cm DBH (Day et al., 2010). Trenching works that sever roots closer than three times DBH, can significantly reduce tree stability when compared to trees that have not had their roots removed (Smiley, 2008). Besides negatively affecting tree stability (Smiley et al., 2014), removing roots can lead to reduced growth (Pretzsch et al., 2016) and vitality (Watson, 1998) as well as altered physiological processes (Benson et al., 2019a).

During greenfield-type site developments, root pruning and root care practices often involve setting aside an area of ground around a tree (a tree protection zone) to define an area of protection, or isolation from construction work (Standards Australia, 2009; British Standards Institute, 2012; Fite and Smiley, 2016). In the urban environment, where trees are often planted in narrow berms alongside roads and footpaths (Jim, 1997), complete isolation from utility or infrastructure works may not be possible, and arboricultural specialists may need to rely on experience or other guidelines when making decisions about root pruning and root care. Occasionally, local government regulatory frameworks contain specifications on root pruning for infrastructure-related works around urban trees (e.g. The City of Charlottesville, 2009; The City of Boroondara, 2010; The City of Rancho Cucamonga, N.D), although empirical evidence supporting these guidelines may be limited (Auckland Council, 2018).

Some guidance documents recommend that root pruning should be offset from tree trunks by no less 2 m (The City of Regina, 2000), five (The City of Bellevue, 2009) or three (Fite and Smiley, 2016) times the trunk diameter. The discrepancies between these guidelines may be due to a lack of research in specific root pruning practices (Costello et al., 2017). Other root pruning guidelines consist of fixed diameter thresholds, above which roots should not ordinarily be removed. The National Joint Utilities Group (2007) in the United Kingdom recommend that this threshold be set at 25 mm in diameter, as too does the British Standards Institute (2012). In some regions of New Zealand, the threshold set by local authorities may permit the removal of roots as large as 80 mm in diameter (Auckland Council, 2018). The disadvantage of using a fixed diameter threshold, is that cumulative root loss relative to tree size cannot be accounted for, as it can be when a trunk diameter-defined trenching offset is adopted.

To account for cumulative root loss using individual roots, the work done in Chapters 5 and 6 has focused on using tree allometry and the principles of the Pipe Model Theory (Shinozaki et al., 1964a, b) to quantify the impact of root severance treatments (Benson et al., 2019a; Benson et al., 2019b) The Pipe Model describes the relationship between the conductive sapwood area in the trunk, and other tissues such as leaves (Grabosky et al., 2007; Lubczynski et al., 2017b) and root systems (Kaipiainen and Hari, 1985; Gould and Harrington, 2008). Chapter 5 revealed significant relationships between the ratio of severed root cross-sectional area to trunk or trunk sapwood cross-sectional areas and the physiological and morphological responses of two different species of *Acer* (Benson et al., 2019b), and Chapter 6 revealed similar results for *Quercus virginiana* (Benson et al., 2019a), when roots were severed in multiple linear trenches at 30 cm from the tree base, and in circumferential trenches made incrementally closer to the tree, respectively. This type of allometric relationship has also been employed when investigating the effects of stability loss following root cutting, revealing significant correlations between the force required to pull standing trees to 1 degree, and the ratio of severed root cross-sectional area (CSA) to trunk CSA ($\sum$(severed root CSA) / trunk CSA at 1.37 m) (Smiley et al., 2014).

Recent root pruning research using *Quercus virginiana* has replicated the types of root severance which may be encountered on a development site, where root loss may occur on all sides (Benson et al., 2019a); for example, due to grade changes. The purpose of this investigation was to replicate the types of root severance which may occur on one side of the tree in a single trench; for example, during utility trenching. Specifically, the objectives were to:

- Investigate the responses of mature landscape trees in response to linear root cutting (trenching), at varying distances (as a function of trunk diameter).
- Investigate how these responses may be affected by the presence of a road.

In doing so, allometry and the relationships between total severed root cross-sectional area and trunk cross-sectional area are used as a means to quantify root pruning doses. The easiest way to account for cumulative root loss is to provide an encroachment threshold - at which root loss should not occur - as several guidance documents do (e.g. Standards Australia, 2009; Fite and Smiley, 2016). However, in some regions of the world, the guidelines provide individual root pruning thresholds, specifying a maximum root diameter (e.g. Auckland Council, 2018). The purpose of investigating the allometric method was to investigate whether this would be a suitable alternative to selective root removal, and to account for cumulative root loss and tree size.

7.3 Materials and Methods

7.3.1 Study sites and trees

The study was conducted using 31 *Quercus virginiana* Mill. trees (mean trunk diameter at 1.40 m = 34.20 cm (δ = 4.40 cm); mean height = 8.86 m (δ = 1.09 m)) planted from 170 L containers into a loamy sand (mean bulk density = 1.43 g/cm^3 (δ = 0.09 g/cm^3), n = 5) in 2005 at the University of Florida's Gulf Coast Research and Education Center, Balm, Florida, USA (27° 45' 41.76" N. 82° 13' 41.01" W).

The trees formed part of the landscape at the research centre and were planted in a lawn area surrounding the grounds (mean spacing = 8.14 m (δ = 5.6 m)). The root zones of the trees had not been altered since planting. A low traffic-volume asphalt road surface ran adjacent to the lawn area that formed the trees' growing environment. The distance from the edge of the road to the tree bases ranged from 2.3 m to 9.1 m. A diagrammatic representation of the experimental site is depicted in Figure 7.1. To account for the presence of the road, the shortest horizontal distance between the road edge and the centre of each tree at its base was measured (Road_D).

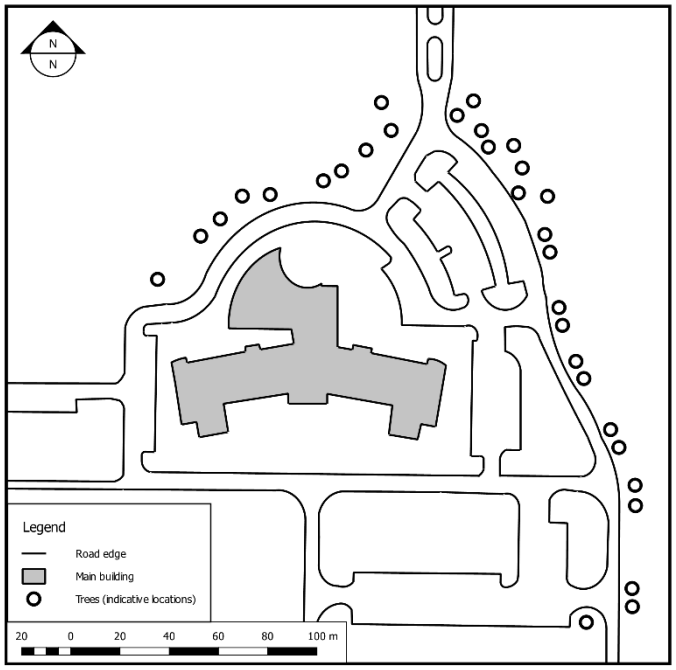

Figure 7.1: Diagrammatic representation of the experimental site depicting approximate tree locations relative to the surrounding features.

Mean annual rainfall at the site is 1,216.62 mm and mean annual temperature is 21.07 °C (FAWN, N.D). Temperature and rainfall were recorded using an on-site weather station with data loggers (Campbell Scientific, Logan, Utah, USA) (Figure 7.2). In September of 2017, the site and surrounding area were affected by Hurricane Irma (Cangialosi, 2018). Though all trees remained standing following the hurricane, they were subjected to high precipitation and sustained winds exceeding 80 km/h.

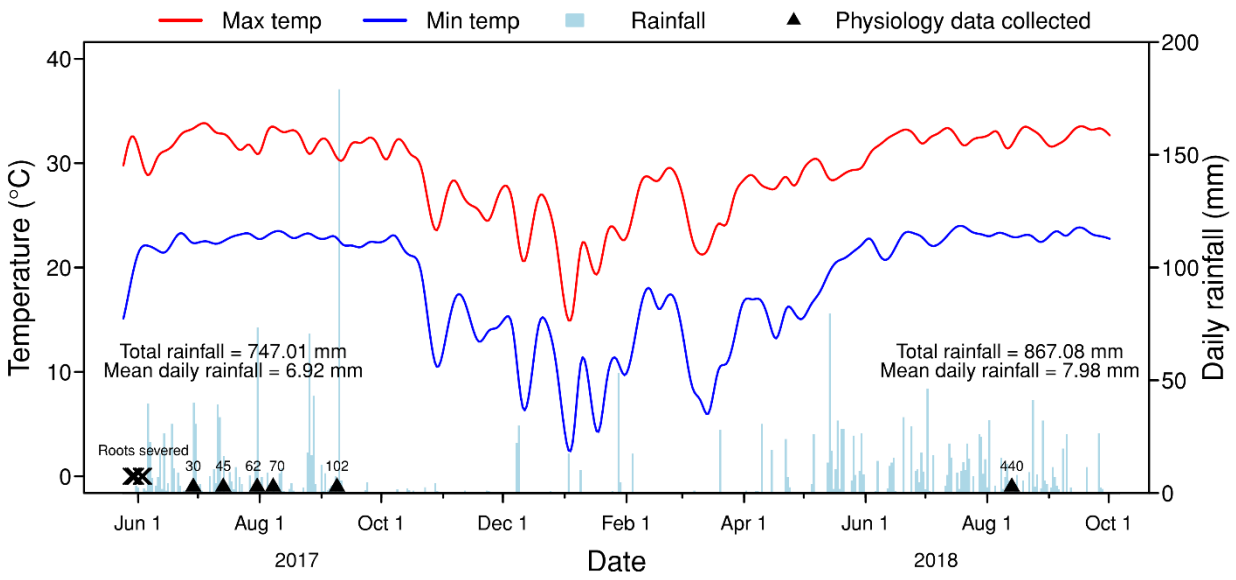

Figure 7.2: Meteorological conditions throughout the experimental period. Triangles denote days on which physiological data were gathered with corresponding numbering denoting the number of days following root severance. Mean daily, and total precipitation in mm for the first 102 days of the study as well as the corresponding period in 2018 are shown.

7.3.2 Root pruning treatments

Trees were randomly allocated to one of three treatment groups with eight replicates of each treatment plus seven controls. Root pruning treatments consisted of a single linear trench, offset from the tree base at a distance equivalent to 3 (3x), 6 (6x) or 12 (12x) times the trunk diameter at 1.4 m.

Between the 31st May and 6th June 2017, trenches ≈ 500 mm deep, ≈ 100 mm wide and ≈ 10.3 m long were excavated using pneumatic soil displacement (Air Spade, Guardair, Chicopee, MA, USA). The ≈ 10.3 m long trench ensured that the maximum chord length of the root zone of the largest tree in the 3x treatment was attained. That is; the 10.3 m trench completely bisected the root zone of all trees in each treatment. The chord lengths (trench length) required for each tree in their treatments were calculated according to Equation 7.1.

$$Chord\ length = 2r\ sin\frac{\varphi}{2} \qquad \text{(Equation 7.1)}$$

Where: r = the root zone radius (Day et al., 2010) plus half of the trunk diameter at ground level and φ = the angle subtended at the tree base by two equally oriented radii (r) forming a sector.

Roots spanning the trenches were severed manually using a sharp saw or loppers during the same period, and fragments of each root were completely excised before filling in the trenches with the original soil material. Following root removal, root cross-sectional area ratios for whole trunk area were determined using Equations 3.1 to 3.3 inclusive. After first estimating the trunk conductive sapwood area of each tree at 1.4 m following the method described in Chapter 4, and applying the correction for *Q. virginiana* (Table 4.2), root cross-sectional area ratios were then expressed as a proportion of the trunk conductive sapwood area at 1.4 m using Equation 3.4. ERT data were gathered from the trees after eleven consecutive days with no precipitation, and so the sapwood area estimates are considered reliable.

The use of pneumatic soil displacement not only enabled roots to be carefully removed from the trees, it also ensured that roots from other nearby treatment or control trees were not inadvertently removed, by tracing their growth and examining morphology where required.

7.3.3 Tree responses to root pruning - Physiology

Pre-dawn leaf water potential (Ψ), stomatal conductance (g_s), leaf temperature (T), chlorophyll fluorescence variables (Fv/Fm and Fv/Fo) and volumetric soil moisture (θ) were measured periodically (approximately every 10 to 14 days, providing the meteorological conditions were favourable) throughout the experimental period (June to September inclusive 2017), and again on August 14th, 2018 (a final measurement date 440 days after root severance). The months of May to October are often described as the 'rainy season' in Florida, with regular (often daily) precipitation events during the afternoon (usually after 14:00). Pre-dawn leaf water potential was measured in situ between 03:00 a.m. and 05:00 a.m. using a pressure chamber (PMS Instruments, Albany, Oregon, USA) from one fully expanded leaf at the second node proximal to the terminus of a new twig from each tree.

Stomatal conductance and leaf temperature measurements were made using an SC-1 leaf porometer (Meter Environment, Washington, USA) calibrated to local conditions using the SC-1 Leaf Porometer Calibration Kit (part# 30425, Meter Environment, Washington, USA). Chlorophyll fluorescence variables were measured using an OS30P+ (Optisciences, Hudson, New Hampshire, USA) following a 45-minute dark adaptation period. Conductance and fluorescence data were gathered from three fully expanded sun leaves at the second node proximal to the terminus of an equivalent number of new twigs between 08:00 a.m. and 11:00 a.m., using the same leaves for both sets of measurements. Only leaves in full sun were sampled. Seasonal mean values for each physiology response for each tree were established using the arithmetic mean of all physiology data gathered during the 2017 growing season (June to September inclusive, 2017).

Using a handheld data-logger (Pro-Check, Meter Environment, Washington, USA) equipped with a soil moisture probe (GS3, Meter Environment, Washington, USA), volumetric soil moisture data were recorded during sunrise (06:00 a.m. – 07:00 a.m.) at two locations (one to the north and one to the south) in the upper 200 mm of the soil approximately 5 m from the trunks of each tree near the outer edge of the 'drip line', where fine root activity was expected (Gilman, 1989; Day et al., 2010; Rahman et al., 2019). Individual soil moisture readings were recorded for each tree and used to derive a site mean water content for each measuring period as well as a seasonal mean value for each tree.

7.3.4 Tree responses to root pruning – Tree growth

Using a conventional measuring tape, trunk circumferences at 500 mm, 1 m and at 1.4 m (breast height) were recorded immediately prior to root severance treatments and again at the end of the 2017 growing season (28th September) and again on 10th August 2018 (436 days after roots were cut). Logistical constraints precluded gathering the growth data for year 2 during September. Shoot growth was measured using 18 new terminal shoots per tree and leaf area was measured using 10 sun leaves harvested from the third node proximal to the terminus of an equivalent number of new twigs from each tree using an LI-3100C leaf area meter (LI-COR Devices, Nebraska, USA). Shoots and leaves were harvested from the upper apical region of each tree, accessed using a mobile work platform.

7.3.5 Statistical analyses

7.3.5.1 Treatment effects

All data were analysed using R statistical software version 3.4.4 (R Core Team, 2018). ANCOVA analyses were undertaken for all physiological and morphological response variables using the root pruning treatment (control, 12x, 6x and 3x) as a discrete variable. Soil moisture was introduced as a continuous variable as well as the distance of each individual tree from the road edge (Road_D). To account for the distance of the road from each tree relative to its size, DBH was also introduced as a continuous variable along with the interaction term with the road (Road_D : DBH). A spatial effect (East or West) of the experimental layout was also tested for. Finding none, data were pooled for analysis.

For physiology responses, individual soil moisture data for each tree on each day that data were gathered were used. For growth responses, a seasonal mean for each tree was established and introduced into the analyses. Models were simplified by stepwise regression using the step() command, specifying “both” in the direction term. The models with the lowest Akaike’s Information Criterion (AIC) value from the stepwise analyses were examined using the Anova() command in the “car” package (Fox and Weisberg, 2011), and any remaining non-significant terms were sequentially removed (beginning with interaction terms). Final models were selected based on the statistical comparison tests between models using the anova() command, selecting the most statistically significant model. Statistically significant differences between treatment and control were identified by the significance of the treatment intercepts from the simplified ANCOVA models, using the summary() command.

7.3.5.2 Continuous variables

Additionally, ANCOVA analyses were undertaken for all physiological and morphological response data using root cross-sectional area ratios at 1.4 m ($Ar_{(BH)}$ and $As_{(BH)}$) as the explanatory variables. Soil moisture, the road and DBH were introduced into the analytical models in the same way as the treatment effects analyses. Stepwise regression, model simplification and selection were undertaken using the step(), Anova() and anova() commands, as was described for the treatment effects.

Unless otherwise indicated, statistical significance for categorical and continuous responses is reported at $p \leq 0.05$.

7.4 Results and discussion

7.4.1 Sapwood areas and root cross-sectional areas

Trunk sapwood areas at 1.4 m for the study trees were between 203.68 cm^2 and 677.24 cm^2 (mean sapwood radius = 8.32 cm (δ = 2.44cm); mean sapwood width % of DBH = 49% (δ = 14%)) and ranging from 71% to 84% of the total trunk cross-sectional area. Root cross-sectional area ratios expressed as proportions of trunk sapwood areas ($As_{(BH)}$) are thus distinct from the ratio of root to whole trunk cross-sectional area ($Ar_{(BH)}$). Root cross-sectional area ratios at breast height (BH; 1.40 m) ($Ar_{(BH)}$ and $As_{(BH)}$) increased as the distance of the treatment to the tree base decreased (12x to 3x) ($p < 0.001$). Across the range of treatments, mean total severed root cross-sectional areas were between 0.05 and 0.19 times the trunk cross-sectional area at 1.4 m ($Ar_{(BH)}$), and 0.11 and 0.44 times the trunk conductive sapwood area at the same height ($As_{(BH)}$). Mean values for $Ar_{(BH)}$ and $As_{(BH)}$ ratios plus or minus one standard error (in parentheses) are presented in Table 7.1. The relationship between total severed root cross-sectional area and treatment is seen in Figure 7.3.

Table 7.1: Mean $Ar_{(BH)}$ and $As_{(BH)}$ ratios for each root pruning treatment ± one standard error (in parentheses). Different letters in a single column denote a significant difference between treatments.

Treatment	$Ar_{(BH)}$	$As_{(BH)}$
12x	0.05 (0.02) a	0.11 (0.04) a
6x	0.08 (0.02) a	0.21 (0.04) a
3x	0.19 (0.02) b	0.44 (0.09) b

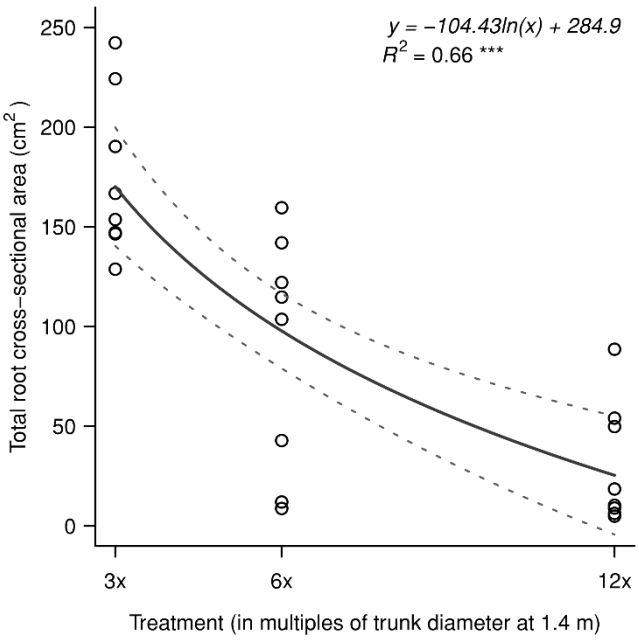

Figure 7.3: Relationship between the distance of the trench from the tree base (treatment) and total severed root cross-sectional area. Dashed lines denote 95% confidence intervals.

7.4.2 Tree physiological responses to root pruning treatments

Pre-dawn leaf water potential was negatively affected by the trenching treatment (Figure 7.4a, Table A 1 - located in Appendix A). Significant differences between control trees and all treatments were observed on one or more of the measuring days. Significant treatment effects were sustained to day 440 only in the 3x treatment (a difference of -0.07 MPa from control trees), which showed statistical separation from the control trees on each of the other five days on which data were gathered.

The negative effects observed in the Ψ response of the root pruned trees are consistent with the responses of other species involved in root pruning (Wang et al., 2014; Dong et al., 2016) and water stress (Epron et al., 1992; Kubiske et al., 1996; Zwack et al., 1998; Fini et al., 2013a) studies, including *Q. virginiana* (Cavender-Bares et al., 2007; Benson et al., 2019a). Whilst there was some variability in the significance between different treatments and the control, it is evident that severe root loss (3x treatment) can have persisting negative effects on leaf water status. Statistical separation between the 12x treatment and the control trees observed on day 102, may have been influenced by fine-root mortality following the hurricane (Herbert et al., 1999).

The photosynthetic process was also negatively affected, particularly on day 45 when the maximum photosystem II (PSII) quantum efficiency (Fv/Fm) was significantly different from the control for the 6x (a difference of -0.01) and 3x (a difference of -0.02) treatments (Figure 7.4b, Table A 2). The variable minimum fluorescence (Fv/Fo) values for the 6x (a difference of -0.47) and 3x (a difference of -0.70) treatments were also significantly different ($p < 0.01$) from the control on day 45 (Figure 7.4c, Table A 3). Negative effects on the photosynthetic mechanism were absent 102 days after treatment, possibly a result of new root growth in the backfilled trenches alleviating some of the initial dysfunction, in combination with the arrival of regular precipitation events and concomitant ground water recharge.

No effect of the root pruning treatment on the g_s response was observed (Table A 4). This is consistent with the anisohydric behaviour of *Q. virginiana* (Beeson, 2014). This type of hydraulic strategy enables stomata to remain open during periods of reduced leaf turgor, to maintain photosynthetic rates (Sade et al., 2012; Martínez-Vilalta et al., 2014). The sclerophyllous nature of the leaves of live oak (Monk, 1987), goes some way towards explaining this behaviour, since it adds rigidity to the guard cells (Lo-Gullo and Salleo, 1988; Oertli et al., 1990; Salleo and Lo-Gullo, 1990).

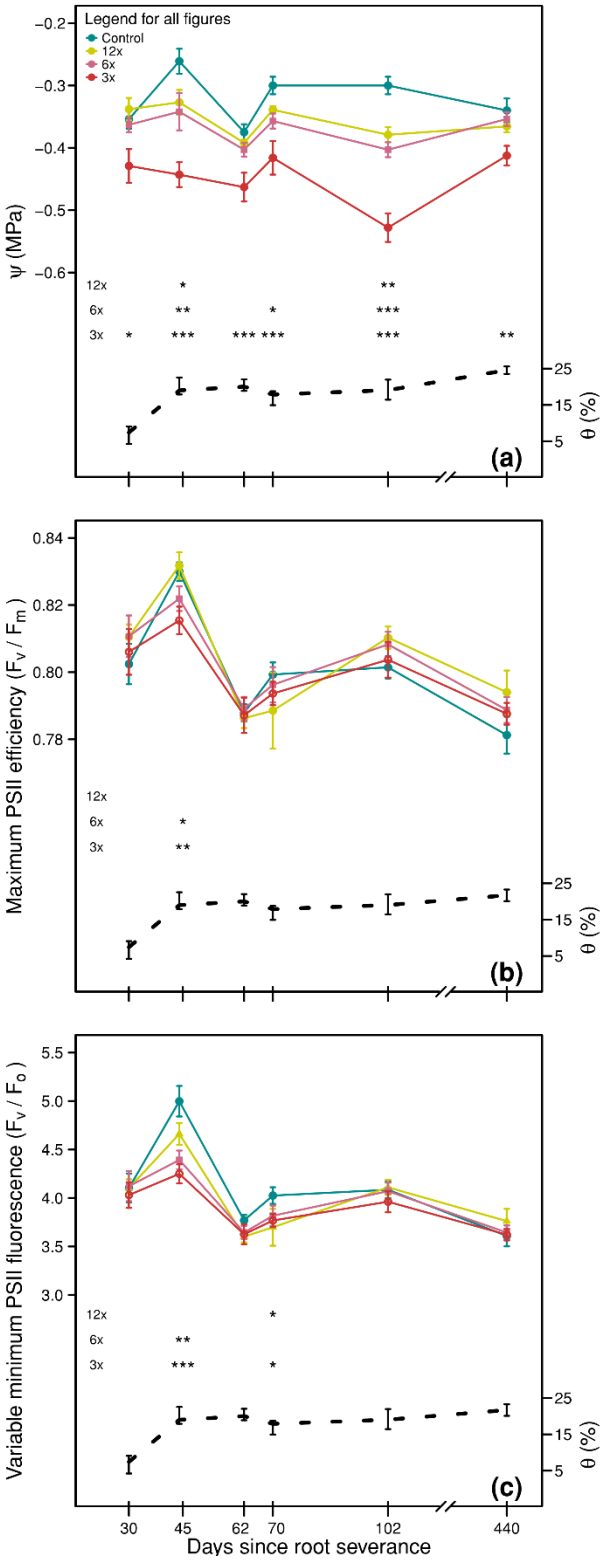

Figure 7.4: Treatment mean pre-dawn leaf water potential (Ψ) in MPa (a); mean maximum photosystem II photochemical efficiency (Fv/Fm) (b); and mean variable minimum fluorescence (Fv/Fo) (c) plotted against number of days since roots were severed. Asterisks in the inset matrix show significant differences between control and treatment (left hand side) on a particular day with the following significance codes; * $p \leq 0.05$ ** $p \leq 0.01$ *** $p \leq 0.001$. Dashed lines denote mean soil water volume (%) throughout the study. Error bars show ± one standard error

7.4.3 Effects of the road on tree physiology

The road (Road_D) was absent from each of the Ψ ANCOVA models, although remained significant for stomatal conductance and leaf temperature responses on day 45 (and leaf temperature on day 70) with a negative slope term (i.e. trees nearer the road had higher g_s and T), when the maximum temperature recorded by the weather station was 34.03 °C (the hottest of all data gathering days). Whilst there may be other factors which could have influenced this behaviour, one possible, and likely reason is that it is due to increased radiant heat over the asphalt surface (Kjelgren and Montague, 1998; Montague and Kjelgren, 2004). Increasing leaf temperature resulted in elevated g_s ($p \leq 0.01$) on each of the data gathering days (data not shown). The photosynthetic responses observed on the same day (which both retained Road_D as a significant variable in the ANCOVA models), may indicate temporary damage to the photosynthetic mechanism, borne from the initial effects of root loss-induced water stress in combination with increased transpiration and leaf temperature (Ashraf and Harris, 2013). The road was absent from the ANCOVA models for g_s and T responses on day 440, which may be due to the evaporative cooling effect of increased precipitation (Figure 7.2) during the 2018 growing season (Lu, 2011; Li et al., 2014). The results suggest that *Q. virginiana* is susceptible to photosynthetic perturbations during periods of increased temperature in conjunction with a root loss-induced water stress.

7.4.4 Tree growth responses to root pruning treatments

The root pruning treatments negatively affected shoot extension and leaf area responses in *Q. virginiana* after one growing season, but not trunk diameter growth (Figure 7.5, Table A 11). Whilst shoot elongation responses in mature trees may exhibit some variability, the root pruning treatments resulted in a 97.29 mm reduction in the 12x treatment, a 146.13 mm reduction in the 6x treatment and a 132.24 mm reduction in the 3x treatment at the end of the first growing season relative to control trees. Leaf area responded in the same fashion, and reductions in leaf area of 2.17 cm^2 in the 12x treatment, 2.72 cm^2 in the 6x treatment and 2.92 cm^2 in the 3x treatment were recorded at the end of the first growing season relative to control trees.

Root removal often negatively affects shoot elongation in the growing season following root loss, although the duration of the effect is variable (Young and Werner, 1982; Ferree, 1989; Autio and Greene, 1994; Khan et al., 1998; Watson, 1998; Fini et al., 2013b; Dong et al., 2016). Reducing leaf area in response to root loss-induced water stress, may serve to reduce overall tree transpiration (Struve and Joly, 1992; Liu and Stützel, 2004; Pallardy, 2008).

Treatment effects on shoot elongation and leaf area responses were absent after the second growing season, supporting the premise that *Q. virginiana* is tolerant to root removal (Matheny and Clark, 1998) and supporting previous results showing variability in the shoot elongation response. Furthermore, since the trenches were backfilled following root severance, it is likely that new root growth contributed towards restoring the root:shoot ratio in the treatment trees, enabling shoot elongation and leaf area responses to return to expected norms (i.e. no statistical separation from control).

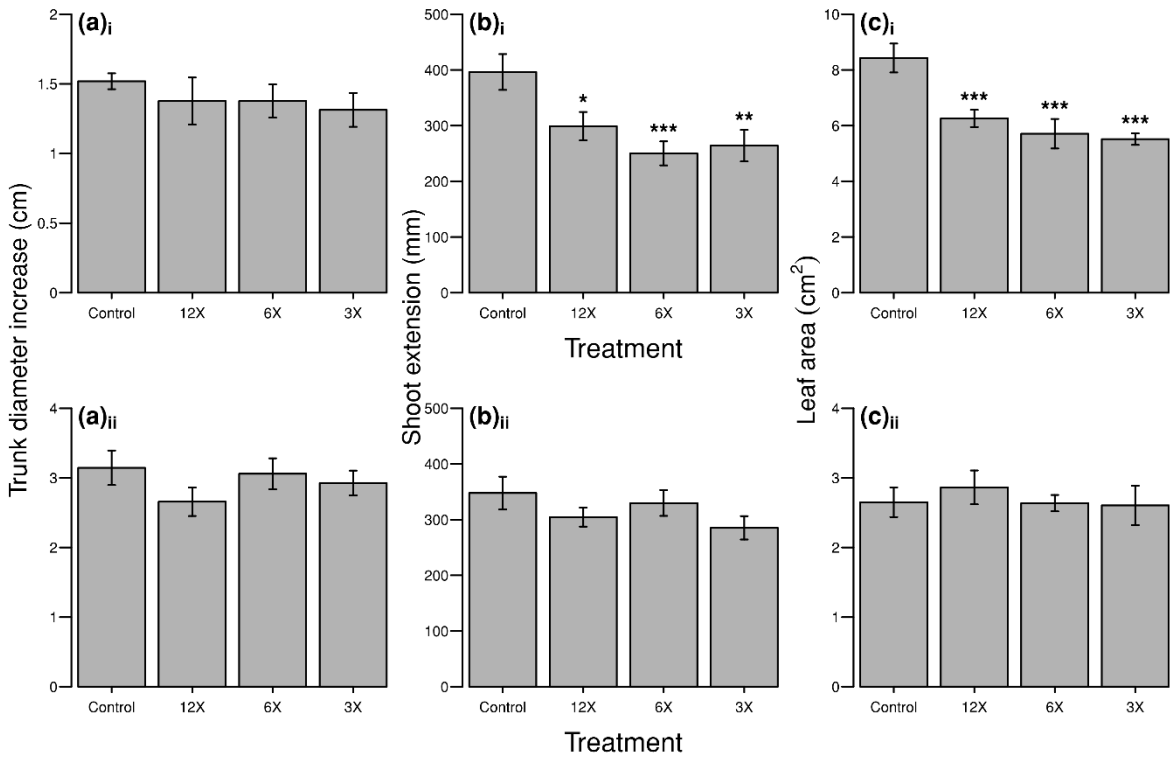

Figure 7.5: Bar plots showing trunk diameter (a); shoot elongation (b); and leaf area (c) growth responses to the root pruning in 2017 (i) and 2018 (ii). Significant differences between treatment and control based on the ANCOVA analyses are denoted by asterisks above each bar with the following significance codes; * $p \leq 0.05$ ** $p \leq 0.01$ *** $p \leq 0.001$. Error bars show ± one standard error (SE).

7.4.5 Effects of the road on tree growth

The road remained significant in the trunk diameter growth models for the 2017 growing season with a positive slope term (i.e. the trunks of trees closer to the road grew less than those further away). Whilst roots directly below paved surfaces may experience favourable conditions (Wagar and Franklin, 1994; Nicoll and Armstrong, 1998), and tree growth may be affected by a range of factors (Cienciala et al., 2016), the response observed may allude to the constraints placed upon trees by the built environment (McPherson, 2001; Grabosky and Gilman, 2004; Celestian and Martin, 2005; Day and Amateis, 2011; Chen et al., 2017; Sand et al., 2018). The road was absent from the 2018 ANCOVA models using the categorical treatment variables.

7.4.6 Tree responses using severed root cross sectional area ratios

The ability of the allometric relationship between trunk and root cross-sectional areas to predict tree responses to root pruning during the growing season immediately following root loss, varied between responses. Scatterplots and regression lines for the relationships between $Ar_{(BH)}$ and $As_{(BH)}$ and Ψ, Fv/Fm and Fv/Fo responses using 2017 seasonal mean data, as well as the data gathered on day 440 are shown in Figure 7.6. The full ANCOVA model statistics are presented in Table A 6 to Table A 10. $Ar_{(BH)}$ was able to account for 75% of the variability (calculated as R^2) in the pre-dawn leaf water potential response ($p < 0.001$) in the growing season following root removal using mean data, revealing explanatory power comparable to that in Chapter 6, when roots were severed in circumferential trenches (Benson et al., 2019a). $Ar_{(BH)}$ accounted for 14% of the Fv/Fm response ($p < 0.05$) and 16% of the Fv/Fo response ($p < 0.05$) in the first growing season following treatment using mean data. Model significance was retained ($p = 0.001$) for the Ψ response on day 440, although is absent for each of the fluorescence responses, possibly illustrating that hydrological response variables are better-suited for this type of investigative purpose, and that $Ar_{(BH)}$ is more useful in the short-term only. No significant relationships are reported between g_s or leaf temperature using the allometric variables.

Scatterplots and regression lines for the relationships between $Ar_{(BH)}$ and $As_{(BH)}$ and the above-ground growth responses are seen in Figure 7.7. Full ANCOVA model statistics are shown in Table A 12. $Ar_{(BH)}$ and $As_{(BH)}$ remained significant in the ANCOVA models for all growth responses in 2017. In combination with soil moisture effects, $Ar_{(BH)}$ accounted for 21% of the variability (R^2) in trunk diameter growth, 18% of the shoot extension response in isolation and 24% of the variability in the leaf area response. Treatment effects on shoot elongation using $Ar_{(BH)}$ and $As_{(BH)}$ remained in 2018 in combination with effects of the road, perhaps indicating a sustained negative effect of built infrastructure on this growth response. Although it is again acknowledged that shoot growth responses may behave with some variability.

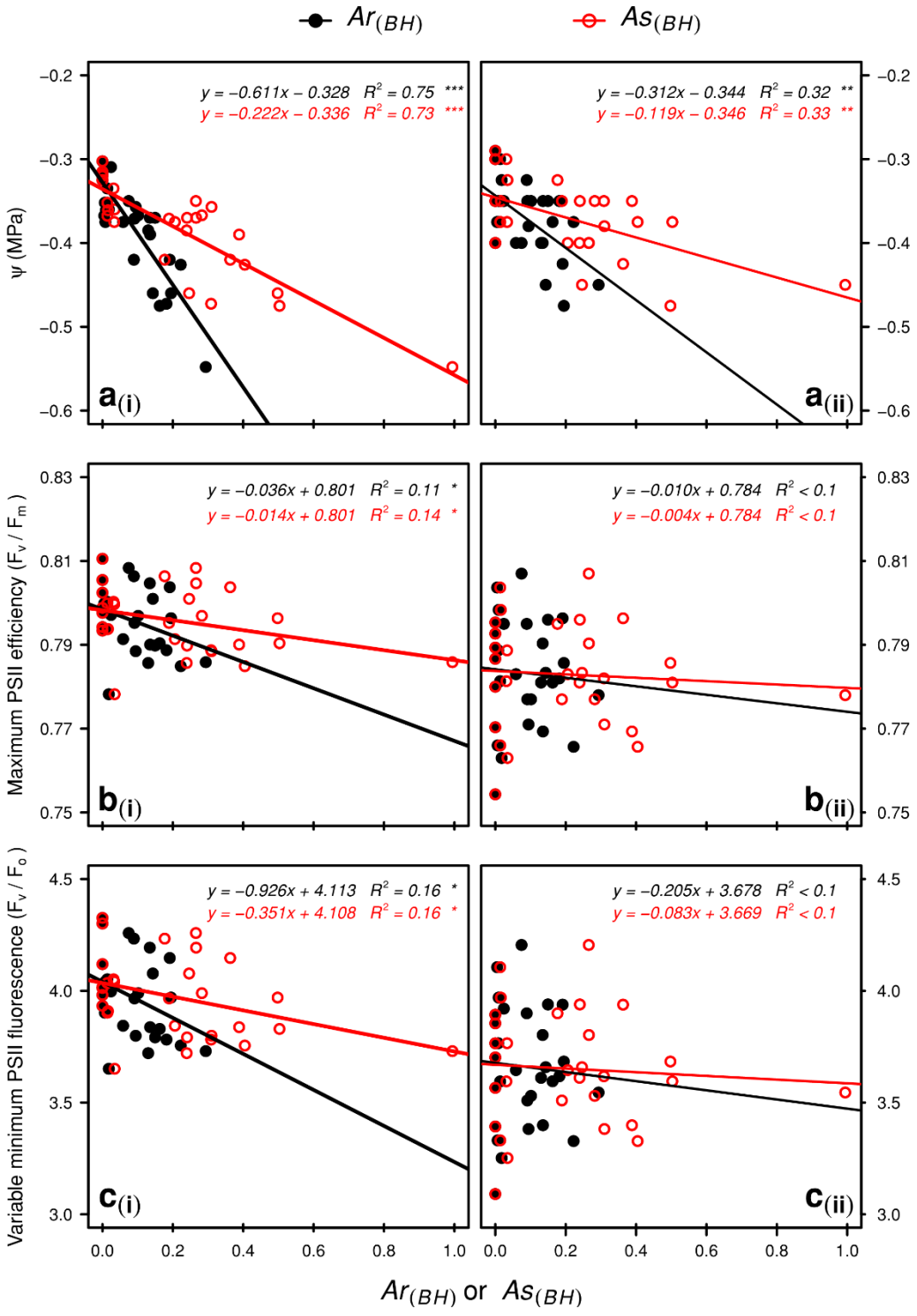

Figure 7.6: Scatterplots and regression lines for pre-dawn leaf water potential (Ψ (MPa)) (a); maximum PSII photochemical efficiency (Fv/Fm) (b); and variable minimum fluorescence (Fv/Fo) (c) responses using 2017 seasonal mean data (i) and data gathered on day 440 (ii) using $Ar_{(BH)}$ and $As_{(BH)}$ as the explanatory variables.

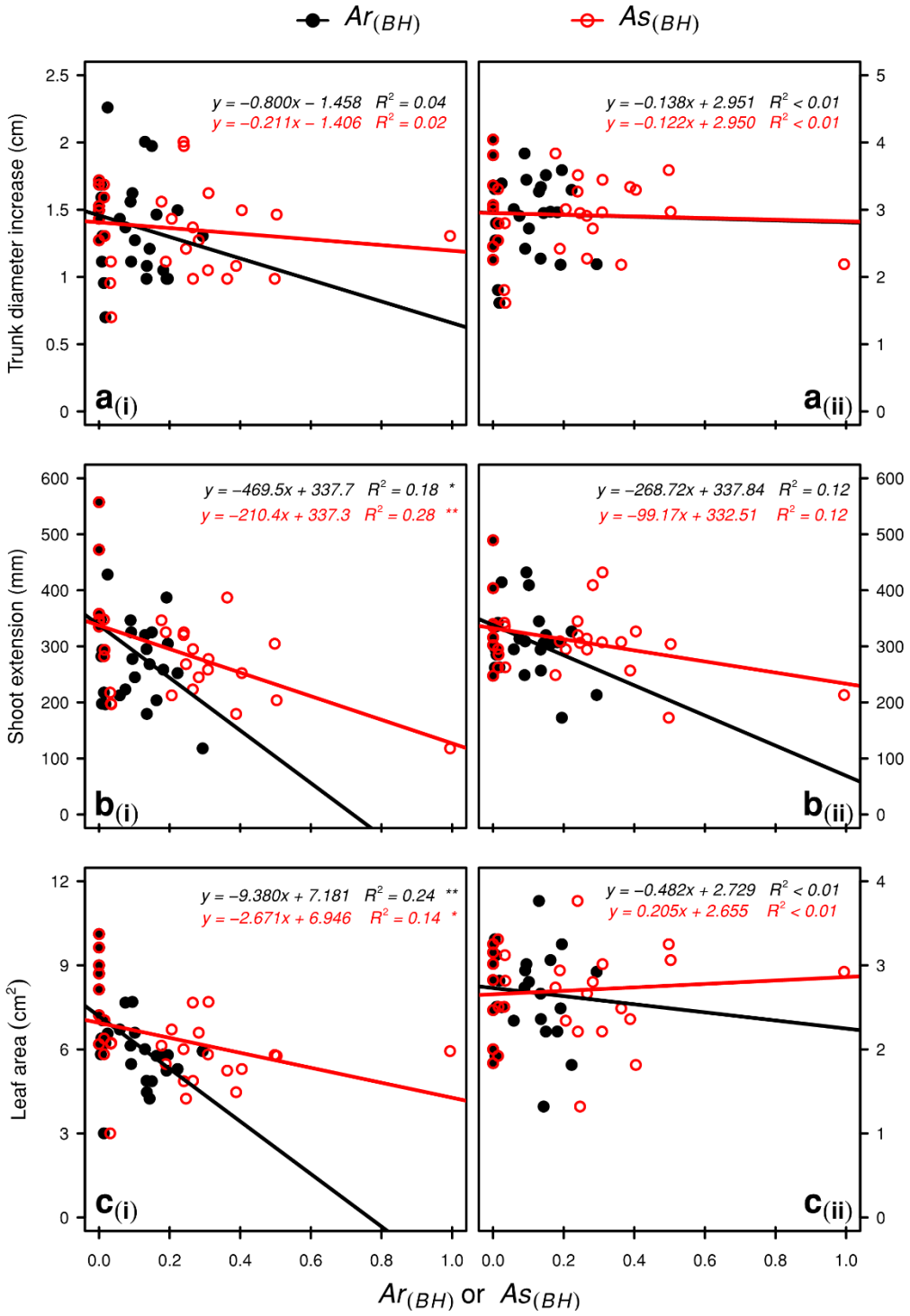

Figure 7.7: Scatterplots and regression lines for trunk diameter (a); shoot elongation (b); and leaf area (c) growth responses to the root pruning in 2017 (i) and 2018 (ii) using $Ar_{(BH)}$ and $As_{(BH)}$ as the explanatory variables.

7.5 Conclusions

Root pruning negatively affected the growth and physiology of *Q. virginiana* in Central Florida. Significant differences were observed between all root pruning treatments and the control for the pre-dawn leaf water potential response, highlighting that root pruning induces water stress in the affected trees. Growth responses were negatively affected by the root pruning treatments, with significant differences between treatment and control emerging at the 12x treatment for leaf area and shoot extension responses after one growing season. The results perhaps highlight the importance of roots peripherally located in the total root system. Although *Q. virginiana* was susceptible to the negative effects of root removal; 440 days after root severance, trees exposed to the 6x and 12x treatments were able to regain physiological function, and tree growth amongst all treatments had returned to expected norms, likely due to new root growth in the backfilled trenches of these less severe treatments.

The allometric variables appeared to be best suited for short-term tree responses, with statistical models losing significance and explanatory power (R^2) over time. The main purpose of using the allometric variables was to investigate a potential alternative to root pruning guidelines which use fixed root diameters, enabling arboricultural practitioners to account for cumulative root loss during selective root pruning practises. In the context of this study, it is simpler to prescribe a trunk diameter-defined offset at which root loss should not occur. Since physiological recovery of the 6x and 12x treatments was observed, it is concluded that linear root cutting should not be undertaken at distances closer than six times DBH in *Q. virginiana,* equating to ≈ 25% root system loss.

Trees which were closer to the road had reduced trunk diameter increases compared to those further away, as well as elevated stomatal conductance and leaf temperature on certain days. Whilst tree growth and physiology may be affected by numerous factors, these results suggest that the presence of built infrastructure in the root zones of *Quercus virginiana* in Central Florida, produces negative effects and may hinder tree growth and development over time.

7.6 Epilogue

The main objective of this experiment was to ascertain how close to a tree a linear root cutting operation could be undertaken without having sustained negative effects, and to augment what is currently known about this type of root severance and its effect on tree stability (e.g. Smiley, 2008). This relates to research question number 3 (How close to a tree can roots be severed in a linear trench before sustained stress symptoms are observed?). It was found that 440 days after root severance, only the 3x treatment was experiencing water stress symptoms, and that the other treatments had showed recovery to within normal limits. If this were to be applied in a practical way, it would be recommended that in order to avoid sustained negative effects on tree health (water stress symptoms), linear root cutting should not be undertaken any closer to the tree than a distance equivalent to six times DBH.

The continuous relationships between $Ar_{(BH)}$ and the response variables again exhibited no curvature, and so a threshold at which the response showed the greatest change was not revealed. What was revealed however, was that only the leaf water potential relationship remained significant after 440 days, although the explanatory power (R^2) and significance (p value) were less than after the first growing season. This highlights the fact that the allometric variable may only be useful in the short term, and also that leaf water potential is likely a good indicator of long-term tree health and water stress effects.

It was also interesting to examine the effect of the road on the tree responses to root loss. The information which was revealed tended to agree with that of others, in that the urban environment can often be inhospitable to tree growth and physiology, having negative effects on both responses.

Chapter 8: The effects of root pruning on tree value

The contents of this chapter have been reproduced from:
Benson, A. and Morgenroth, J. (2019). Root pruning negatively affects tree value: A comparison of tree appraisal methods. Urban Forestry and Urban Greening. 43, 126376 10.1016/j.ufug.2019.126376.

8.1 Preamble

This investigation uses the morphological data of the trees from the previous three chapters (excluding the *A. negundo* at Totara Park) prior to, and one growing season after root removal, to ascribe each a monetary value using tree valuation methods. The *A. negundo* were excluded because of the way the statistical analyses were undertaken (linear mixed effects modelling). Excluding these trees achieved greater clarity in the presentation and interpretation of the results as this relates to the differences between treatment types. That is; the random effect in the analyses is the treatment type (i.e. multiple trenches (Chapter 5), circumferential trenches (Chapter 6) and a single trench (Chapter 7)), rather than a location, or species.

Root pruning can affect the growth, health and longevity of trees. These characteristics are frequently seen as criteria in tree valuation methods. The purpose of this investigation was to answer research question number 4.

Research question 4: How does root pruning affect tree monetary value when trees are valued using common valuation methods?

The materials and methods section in this chapter has been edited from its original form to avoid repetition of the methods previously described in sections 3.1 and 3.2.

8.2 Introduction

In recent years, arboricultural practitioners have developed various methods of assigning monetary values to trees to financially quantify the various benefits which they provide. Assigning a monetary value to a tree can be of use to insurers in compensation and litigation matters (Hegedüs et al., 2011; Komen and Hodel, 2015), or for local authorities who may wish to impose bonds on developers undertaking alterations around a highly-valued tree. It is also useful to assign value based on ecosystem services, to convey the values of trees in tangible ways to decision-makers (Nowak, 2018). Multiple methods for appraising tree value exist internationally (Ponce-Donoso et al., 2017). Several of these approaches use formulae to either award points which are later converted to a monetary value, or to first establish a value based on replacement cost, and then adjust it based on tree attributes using mathematical operations (Watson, 2002). These types of parametric methods of appraisal are the most suitable for appraising urban trees in an international context (Ponce-Donoso et al., 2017; García-Ventura et al., 2018). Invariably, tree dimensions are considered in the appraisal, with greater scores awarded to larger trees. In contrast with other elements of urban infrastructure such as buildings and street furniture such as benches – the value of which depreciates with age (Pursell, 1984; Pallot, 1997) – whilst trees remain healthy, they spend much of their lives appreciating in value as they increase in size and age (McPherson, 2007). Similarly, tree vitality and longevity are criteria involved in the appraisals, and so where biotic or abiotic factors negatively affect these attributes, concomitant reductions in overall score and associated monetary value could be expected.

Construction work in the urban environment to accommodate population growth and engineering requirements (Chi, 2012; Duranton and Turner, 2012; Chen et al., 2014), frequently involve excavations in the public transport corridor (Rogers et al., 2012). These types of ground alterations can place nearby urban trees at risk of root damage, leading to partial destruction or removal of root systems (Jim, 2003; North et al., 2017). Root severance can negatively affect tree growth (Fini et al., 2013b; Pretzsch et al., 2016) and vitality (Hauer et al., 1994; Watson, 1998; Benson et al., 2019b), which ultimately has the potential to negatively impact tree value.

By examining the effects of root removal (such as reduced growth and vitality) over the course of a growing season, the objectives of this study were to:

- Investigate whether root removal affected tree value, by using four common parametric tree appraisal methods.
- Compare the effectiveness of each of the four methods for this purpose.

8.3 Materials and methods

8.3.1 Study sites, trees and tree mensuration

This investigation used the trees at Tāmata Maples, GCREC and PSREU, described previously in Chapters 5, 6 and 7. Prior to root manipulations, trunk circumferences at breast height (≈ 1.4 m) were measured with a conventional measuring tape following published mensuration methods (British Standards Institute, 2012). Tree heights were measured with a height stick (Tāmata Maples) or a digital laser hypsometer (Nikon Forestry Pro, Nikon, Tokyo, Japan) (GCREC and PSREU). It was not possible to see the bottom and top of every tree at Tāmata Maples owing to the planting density, and the height stick was not available in Florida, nor would it have been long enough to reach the tops of the trees. Tree crown spreads were measured in the north to south and east to west directions using a measuring wheel to establish a mean diameter for each tree. The same mensuration was undertaken at the end of the study, with the exception of crown spread, using the same tools / devices. Two of the appraisal methods adopted in this investigation rely on assigning tree value using either crown area (Helliwell) or tree volume (Burnley). Although crown diameter can be a key indicator of tree value (Sánchez-Medina et al., 2017), the crowns of multiple trees at each site overlapped, and so crown diameters may have been influenced by phototropic growth patterns. Although it is possible that root loss may have influenced crown size, to remove the possibility of measuring errors which may have affected the final crown diameter and thus the final appraised value, it was assumed that crown diameter did not change following root loss. A summary of each root pruning investigation, its location, species used, root pruning treatments and mensuration periods are presented in Table 8.1.

Table 8.1: Summary of treatments and study durations

Study	Location	Species	Root pruning treatments	Replicates (*n*)	Study duration (days)
Tāmata Maples	Matangi, Waikato, New Zealand	*Acer palmatum* 'Bloodgood'	Linear trench at fixed distance (30 cm). · Control (no trench) · (T1) One side · (T2) Two sides · (T3) Three sides · (T4) Four sides 1.50 m long and 500 mm deep	20	129
GCREC	Balm, Florida, USA	*Quercus virginiana*	Linear trench at a trunk diameter-defined distance. · Control (no trench) · (12x) 12 times DBH · (6x) 6 times DBH · (3x) 3 times DBH 10 m long and 500 mm deep	8 (7controls)	114
PSREU	Citra, Florida, USA	*Quercus virginiana* 'SDLN'	Circumferential trench with a trunk diameter-defined radius. · Control (no trench) · 15x (trench at 15 times diameter at 1 m) · 12x (trench at 12 times diameter at 1 m) · 9x (trench at 9 times diameter at 1 m) · 6x (trench at 6 times diameter at 1 m) · 3x (trench at 3 times diameter at 1 m) Trenches 500 mm deep	3	100

8.3.2 Description of tree appraisal methods

Four common parametric tree appraisal methods were used in this investigation, those being the CTLA Trunk Formula Method (USA), the Revised Burnley Method (Australia), the Helliwell Method (United Kingdom) and the Standard Tree Evaluation Method (New Zealand). Tree appraisals at both sites were carried out by the same qualified arboricultural professional, to remove the effect of inter-appraiser variability from the valuations. The single appraiser had previously been privy to the treatments at each site, however at the time the final appraisals were made, all identifying features of the treatments were absent. All currency conversions shown were accurate on 9th March 2019.

8.3.2.1 Guide for Plant Appraisal – 9th Edition (Council of Tree and Landscape Appraisers, 2000)

The CTLA Trunk Formula Method establishes value initially using the cross-sectional area of the tree trunk. The cost per unit trunk cross-sectional area is first ascertained by researching the cost of the largest commonly available transplantable tree found in regional nurseries and dividing that cost by the trunk cross- sectional area of that tree. The basic cost is extrapolated by multiplying the unit cost by the difference in trunk cross-sectional area between the nursery tree size and the subject tree size, and then adding the cost of procuring and installing the nursery tree. The basic cost represents the cost to reproduce a 'notionally ideal' tree that is free of defects. This is then reduced by factors, including species quality (determined by a panel of local experts accounting for climate-suitability, pest pressure, invasive potential, and other factors), tree condition and location in the landscape (scores of 0 to 1 for each factor). The appraised value using the CTLA Trunk Formula Method is derived according to Equations 8.1 and 8.2.

$$Appraised\ value = (basic\ tree\ cost) \times species \times location \times condition \quad \text{(Equation 8.1)}$$

where;

$$Basic\ tree\ cost = (\Delta TA \times unit\ tree\ cost) + installed\ tree\ cost \quad \text{(Equation 8.2)}$$

Species ratings incorporate species suitability in regional climates and consider United States Department of Agriculture (USDA) hardiness zones. USDA hardiness zones for Tāmata Maples were obtained using analysed third-party meteorological data from weather stations around the country (Liddle Wonder, 2005). Hardiness zones for GCREC and PSREU were obtained from the USDA website (United States Department of Agriculture, 2012). The region in which the trees in Tāmata Maples was located was hardiness zone 9, which was also true of the trees in the two Floridian studies. Accordingly, species ratings for all species were ascertained using the most recent species ratings obtained from the Florida Chapter of the International Society of Arboriculture (ISA) (Florida ISA, 2016).

Unit tree costs were established using mean values from local nurseries (*Q. virginiana*; US$10.60/cm^2, (n=5), *A. palmatum*; NZ$14.22/cm^2 (US$9.68/cm^2), (n=8)). Installed tree costs for *Q. virginiana* were ascertained from one supplier who offered a planting service. Installed costs for *A. palmatum* were established using the local municipal contract rate (correct at 2018) for street tree planting including site preparation (Hamilton City Council, 2018b).

Factors which may be affected by root removal using the CTLA Method are those in the "Condition" criterion. Tree condition is separated into discrete units such as roots, trunk, branches, twigs and leaves. For roots, trunk and branches, points are awarded (1-4) in sub-categories for "structure" and "health". For twigs and leaves, there are no sub-categories. Maximum points (4) are awarded for "No apparent problems" and minimum points (1) are for "Extreme problems". The two intermediary steps are "Minor" (3) and "Major" (2) problems. The roots of control trees at each study site were assumed to have "No apparent problems" and were awarded maximum points in the structure and health sub-categories. With increasing root removal across treatments at each study site, points were systematically deducted. The minimum points (1) in the roots criterion were awarded to the 3x treatment at PSREU. Any concomitant effects of root removal, such as premature leaf abscission or dead twigs, were assessed on an individual tree basis.

8.3.2.2 The Revised Burnley Method (Moore and Arthur, 1991)

The Burnley Method follows a similar structure to that of the CTLA Trunk Formula Method, in that the tree is first valued based on size - although in the Burnley Method, it is the volume of the tree that is assigned a unit value, based on it being considered as a uniform cone (using mean canopy radius and tree height as input parameters). Again, the value of commercially available nursery trees are valued in this way to derive a unit volume value for the same species as the appraised tree, which is then adjusted by 'modifiers' (0-1) for life expectancy (E), form and vigour (F) and location (L). The appraised value using the Burnley Method is derived according to Equations 8.3 and 8.4.

$$Appraised\ value\ = base\ value\ \times E\ \times F\ \times\ L \qquad \text{(Equation 8.3)}$$

where; $Base\ value\ = unit\ tree\ cost\ (\$/m^3) \times\ tree\ volume\ (m^3)$ (Equation 8.4)

For this investigation, unit tree costs were established using mean values from the same local nurseries as were used in the CTLA Method (*Q. virginiana*; US\$66.70/cm^3 (n=5), *A. palmatum*; NZ\$179.77/cm^3 (US\$134.56/cm^3) (n=8)).

The factor which may affect tree value following root removal using the Burnley Method, is "Life expectancy". The Burnley Method uses a series of bands, or ranges in the "Life expectancy" category. Each band spans nine years, e.g. 10-19 years. Maximum points (1) are awarded to trees with a life expectancy ≥ 50 years and minimum points (0.5) are awarded to trees with life expectancies <10 years. The resolution of the point scale is 0.1. Control trees were assumed to have life expectancies ≥50 years, and points were systematically deducted across treatments with increasing root removal intensity. The minimum points awarded were 0.8 (30-39 years) for the 3x treatment at PSREU.

8.3.2.3 Amenity valuation of trees and woodlands (Helliwell, 2008)

The Helliwell Method, as it is most commonly referred to, assigns points (0-8) to the appraised tree based on attributes: size (S), life expectancy (E), importance in the landscape (I), the extent of surrounding tree cover (P), the tree's suitability in the landscape (L) and overall form (F). The product of the points from each category is then multiplied by a monetary conversion factor (£), determined annually by the British Arboricultural Association and Tree Council. As of January 2018, the monetary conversion factor for individual trees was £33.01 (US$42.97) (The Arboricultural Association, 2018). The appraised value using the Helliwell Method is derived according to Equation 8.5.

$$Appraised\ value\ = S \times E \times I \times P \times L \times F \times £ \qquad \text{(Equation 8.5)}$$

As with the Burnley Method, the factor which may affect tree value following root removal is "Life expectancy". Helliwell too, uses bands, although the ranges differ. Minimum points (0) are for trees with a life expectancy <2 years and maximum points (4) are for trees with life expectancies >100 years. Whilst the ranges differ from those in the Burnley Method, estimations for life expectancy remained consistent following the root removal, and points were awarded accordingly in the corresponding Helliwell band.

8.3.2.4 A Standard Tree Evaluation Method - STEM (Flook, 1996)

The STEM approach is the most commonly used method of tree valuation in New Zealand, and many local authorities use this method to ascertain whether a tree is suitable for inclusion on notable tree registers (The Royal New Zealand Institute for Horticulture, 2003), often by setting a point threshold for consideration. The method awards points (3-27 in increments of 6) in two assessment categories, each with five criteria. First, a condition assessment: form, occurrence, vigour / vitality, function (e.g. ecosystem services), and age. Second, an amenity assessment: stature, visibility, proximity to other trees, role (its visual contribution to the aesthetic) and climate (any positive or negative effects on microclimate).

The sum of the points (the evaluation score (ES)) is first multiplied by the wholesale cost of a five-year-old replacement tree of the same species. Site preparation and all associated planting costs are summed and added to that value. The annual maintenance cost of the appraised tree is then multiplied by the age difference between the replacement nursery tree and the appraised tree and added to the dollar value. A percentage margin may then be added to the final value depending on the circumstances to reflect retail cost. The practice note suggests doubling; however this would be uncommon (Cadwallader, 2019a). The addition of a sales tax may be a more suitable means to accurately reflect market values; this approach was used in this investigation. The appraised value using STEM is derived according to Equations 8.6 and 8.7.

$$\text{Evaluation score} = \text{condition} + \text{amenity} \qquad \text{(Equation 8.6)}$$

$$Appraised\ value\ = \begin{bmatrix} (ES\ \times\ cost) + (planting\ costs) + \\ (\Delta age\ \times\ annual\ maintenance\ cost) \end{bmatrix} + \text{sales tax} \qquad \text{(Equation 8.7)}$$

Wholesale tree costs were established as the mean of n trees from each nursery (*Q. virginiana;* US$856.57, (n=5). *Acer palmatum;* NZ$141.25 (US$108.51) (n=8)). Annual maintenance costs for *Q. virginiana* were established from budgetary information received from The City of Tampa's Parks and Recreation Department relating to annual expenditure on municipal street tree maintenance (US$12.63 per tree) (The City of Tampa, 2018). For the *Acer*, the same information was received from Hamilton City Council (NZ$50.00 (US$38.41) per tree) (the nearest major city to the study site) (Hamilton City Council, 2018b). Planting costs were established in the same way as the CTLA Method.

The factor affected by root pruning using STEM would be "Vigour / Vitality". STEM uses ordinal scales with qualitative descriptors of tree vitality. The default position for control trees in this investigation was 21 points ("Very Good" vitality). Points were deducted from trees displaying reduced vitality, i.e. reduced growth compared to controls or the visual appearance of reduced vitality (premature leaf abscission, twiggy deadwood). The minimum points awarded were 9 ("Some" vitality) in the 3x treatment at PSREU.

A breakdown of the appraisal criteria and the awarded points for each method can be found in Table 8.2. Apart from setting some baseline values for treatments in certain criteria, the effects of root loss (reduced vitality, premature leaf abscission and reduced growth etc.) on each of the trees was assessed individually.

Table 8.2: Breakdown of scoring process for each appraisal method.

Study		CTLA		BURNLEY	HELLIWELL	STEM
	Treatment	Roots (health)	Roots (structure)	Life expectancy	Expectancy	Vigour / Vitality
Tāmata Maples	Control	4	4	1	3	21
	T1	3	3	0.9	3	15
	T2	2	2	0.9	3	15
	T3	2	2	0.9	3	15
	T4	1	1	0.9	3	15
GCREC	Control	4	4	1	3	21
	12x	3	4	1	3	21
	6x	3	3	0.9	3	15
	3x	3	2	0.8	2	15
PSREU	Control	4	4	1	3	21
	15x	3	4	1	3	21
	12x	3	4	1	3	21
	9x	2	3	0.9	3	15
	6x	1	2	0.8	2	15
	3x	1	1	0.8	2	9

Note: All other criteria involved in each method which are not shown, were awarded points objectively on a case-by-case basis, based on the visual appraisal and known growth responses following root loss. In the case of the Vigour / Vitality criterion using STEM, the default points are shown. Further points may have been deducted based on visual cues of reduced vitality, i.e. premature leaf abscission and the emergence of dead twigs, but only where this would have further reduced the qualitative description of the tree's vitality.

8.3.3 Statistical analyses

At each site, for each root pruning type, trees were valued using each method prior to root removal (at the start of the summer growing season) and again at the end of the growing season following root severance (Table 8.1). Initial and final values were compared, and the response data were recorded as a percentage change in value (Δ value (%)) using each method as well as the average of all four.

All data were analysed using R statistical software version 3.4.4 (R Core Team, 2018). Unless otherwise indicated, all tests for significance are reported at $p \leq 0.05$.

8.3.3.1 Treatment effects

The use of ANOVA requires data to meet several assumptions. In this investigation, a Shapiro-Wilks test and visual inspection showed that residuals failed to meet normality assumptions, thus precluding the use of ANOVA. Instead, a non-parametric Kruskal-Wallis test was used to test for statistical differences in means owing to treatment effects. Post-hoc multiple comparison testing was undertaken via the dunnTest() function in the "FSA" package (Ogle, 2018) with Bonferroni correction.

8.3.3.2 Continuous variables

Four continuous independent variables were used to quantify the root loss for each tree at each study site. The purpose of exploring these variables was to test their effectiveness at explaining the response variable. Each independent variable can be measured or calculated by arboricultural practitioners using simple tools such as tape measures or Vernier callipers and could be applied in a practical application.

Maximum root diameter – The diameter of the largest severed root in millimetres.

% TPZ removal – A percentage loss of each tree's tree protection zone (TPZ). TPZs were calculated using a 15:1 ratio of trunk diameter at breast height (DBH) (Benson et al., 2019a) following the mensuration methods and recommendations set out in BS5837:2012 Trees in Relation to design, demolition and construction: Recommendations (British Standards Institute, 2012) and the percentage area lost through root removal was calculated using algebraic operations (Appendix B).

Total number of severed roots – The total number of roots measuring 2 mm or more in diameter (Lyford, 1980) severed from each tree.

$\boldsymbol{Ar_{(GL)}}$ – The Area Ratio of severed roots expressed as a proportion of the trunk area at ground level (Equations 3.1 to 3.3 inclusive).

Linear mixed effects models were established using the lmer() command in the "lme4" package in R (Bates et al., 2015). Fixed effects were the continuous variables described above, and the random effect was the individual study (1, 2 or 3). Random effects were investigated in each model with random slope and intercept terms. Models were described using the Akaike's Information Criterion (AIC) value as well as slope and intercept values for each effect.

8.4 Results

8.4.1 Treatment effects

Bar plots for the Δ value (%) response to each treatment using each of the four appraisal methods for each study are depicted in Figure 8.1. At each site, root pruning negatively affected tree value in one or more treatments. At Tāmata Maples, CTLA responded with a broad range of percentage value change (6.28% to -18.04%) and statistical separation from control for all treatments was observed. Burnley responded almost uniformly across all treatments as did STEM, and both methods revealed statistical separation from the control for all treatments. CTLA and Burnley methods yielded positive increases in value for control trees (CTLA: 6.28%%. Burnley: 3.42%) which were absent using the STEM method. Helliwell was insensitive to the treatment at Tāmata Maples, showing no change in value for all treatments and control. On average, root pruning treatments at Tāmata Maples yielded negative effects across all treatments (-5.68% to -8.41%) with statistical separation from control in all cases. Control trees were observed to increase in value by 1.66% using the average of the four methods.

At GCREC, CTLA again showed statistically significant differences between treatment effects, with statistical separation between the 6x and 3x treatments and the control. Using Burnley, the 12x treatment showed a 7.52% increase in value; compared to the 9.32% increase of the control. Statistical separation was not observed. The 6x and 3x treatments were not significantly different from each other but were different from the control. An increase in value was seen in the control trees (9.29%) using the Helliwell Method as well as the 6x treatment (2.5%), although this is due to a single tree within this treatment group increasing in growth sufficiently to place it into the next size band, thus affording it more points. Statistical separation from control and each of the other treatments was only observed for 3x. STEM produced minor increases in value for control (1.17%) and 12x (2.04%) treatments and reductions for 6x (-7.54%) and 3x (-5.66%) treatments. The 6x and 3x treatments were significantly different from the control trees and the 12x treatment, but not each other. At GCREC, the average of all four methods revealed increases in value for control (7.09%) and 12x (2.00%) treatments. The 6x treatment lost 3.31% of its initial value and the 3x treatment lost 14.50% of its initial value. Statistical separations between the control and the 6x and 3x treatments were observed.

At PSREU, CTLA again yielded a broad range of Δvalue (%) (5.66% to -22.40%). Burnley also yielded increases in value in control (4.44%), 15x (4.62%) and 12x (1.66%) treatments, where the other treatments lost value (-6.37% to -18.73%). Trees assessed with the Helliwell Method at PSREU produced no change in value for control, 15x, 12x and 9x treatments. 6x and 3x treatments lost 33.33% and 27.78% of their original value respectively, although yielded no statistical separation from control. STEM also produced increases in value for control and the 15x treatment (2.72%), with zero change in the 12x treatment. The average of all four methods revealed a wide range of values (3.20% to -21.01%). Statistical separation from the control was only observed for the 3x treatment using the CTLA Method as well as the average of all four.

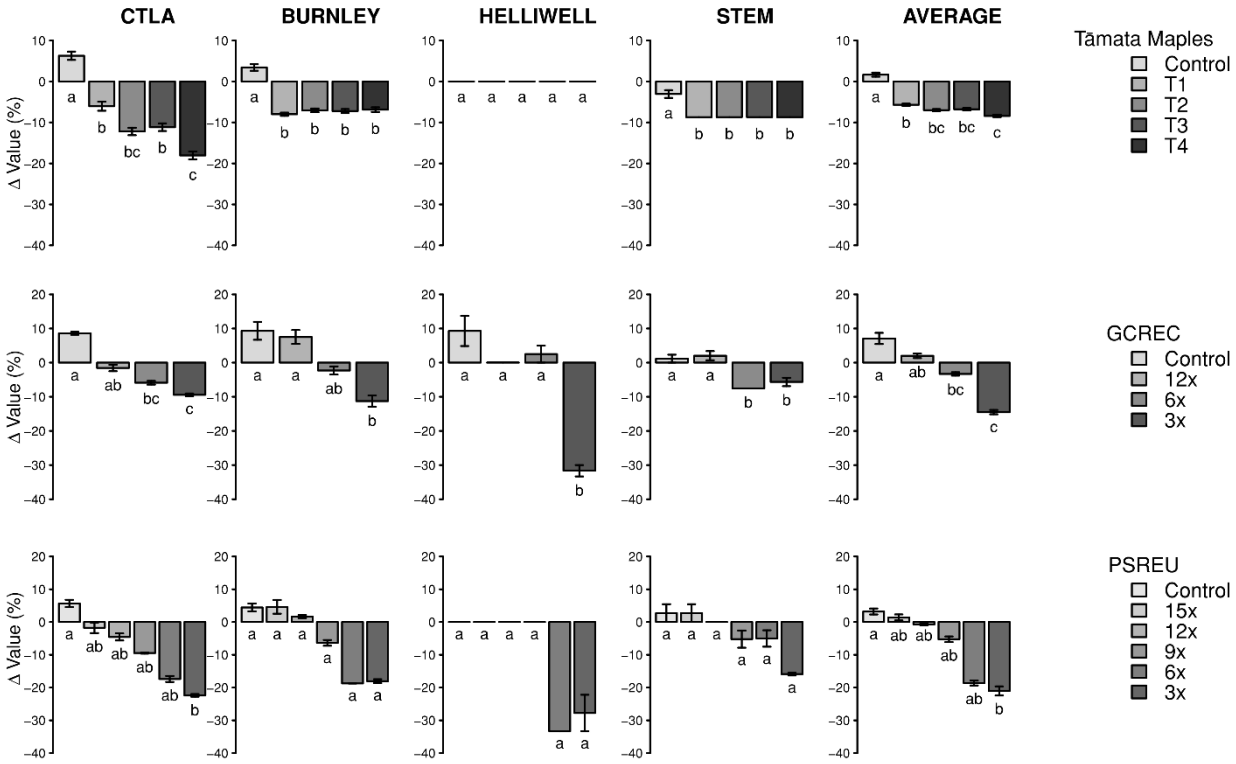

Figure 8.1: Bar plots for treatment effects on percentage change in tree value (Δ value (%)) for CTLA, Burnley, Helliwell and STEM valuation methods as well as the average of all four. Error bars show ± one standard error. Different letters denote statistical separation at $p \leq 0.05$.

8.4.2 Continuous variables

The regression relationships for each of the mixed models are seen in Figure 8.2 and the corresponding statistical information is presented in Table 8.3. The percentage loss of tree protection zone (TPZ) was the best performing variable for predicting changes in tree value using the CTLA, Burnley and STEM methods, as well as the average of all four, characterised by the lowest AIC value. The allometric approach ($Ar_{(GL)}$) performed best at explaining change in value using the Helliwell model, although was again followed by % TPZ loss based on the AIC values. There was little correlation between $Ar_{(GL)}$ and the CTLA response, predominantly at Tāmata Maples. Significant slope terms for the fixed effect were revealed using maximum root diameter for the Burnley and STEM methods as well as the average. Percent TPZ loss also revealed a significant slope term using the CTLA Method.

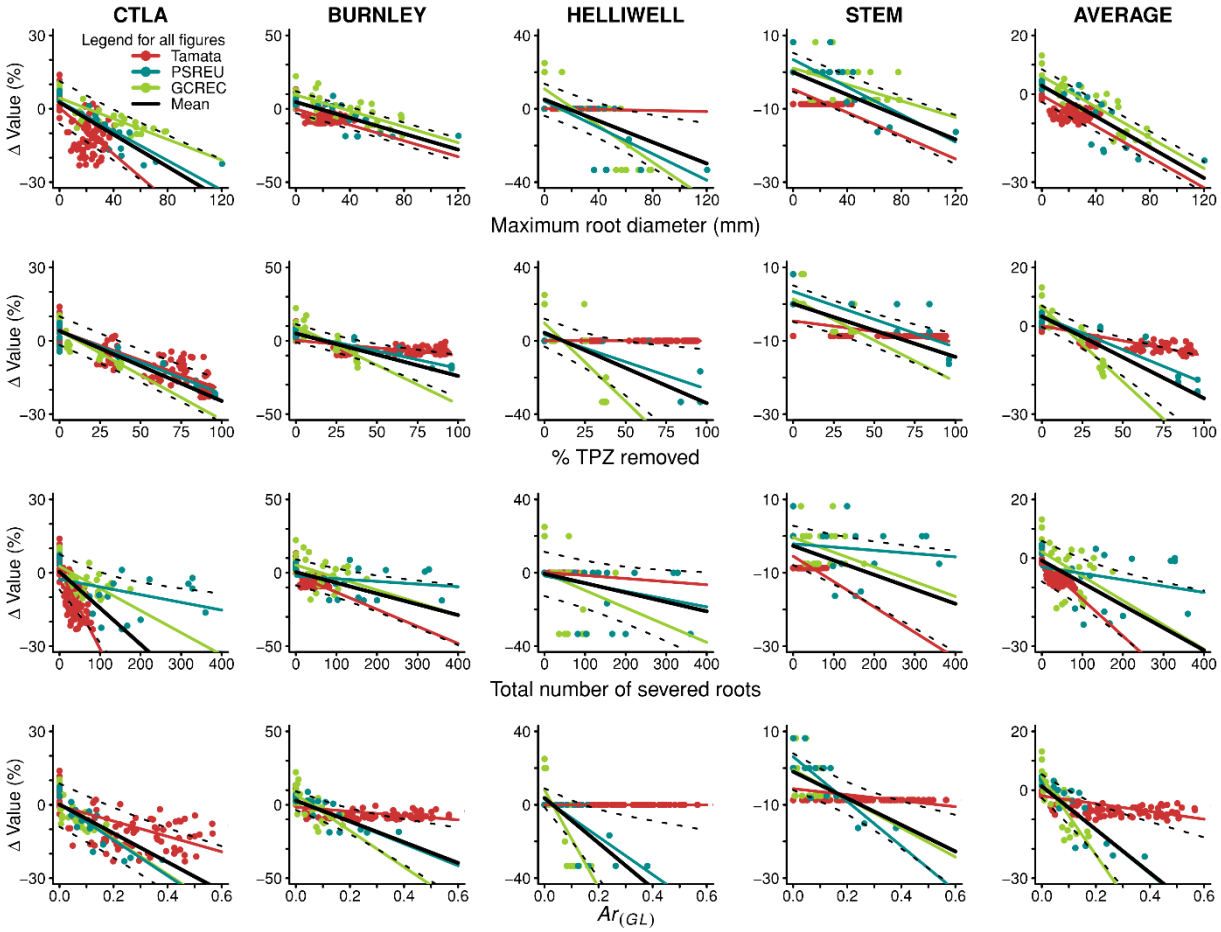

Figure 8.2: Linear mixed effects relationships between maximum severed root diameter (mm) (upper row), % tree protection zone (TPZ) loss (second row), total number of severed roots (third row) and $Ar_{(GL)}$ (bottom row) and percentage change in tree value (Δ value %) for CTLA, Burnley, Helliwell and STEM valuation methods as well as the average of all four. Dashed lines show 95% confidence intervals about the mean.

Table 8.3: Mixed effects model statistics for maximum root size (mm) , percent tree protection zone (TPZ) removal, total number of roots severed and root cross-sectional area ratio ($Ar_{(GL)}$) for each valuation response (CTLA, Burnley, Helliwell and STEM) as well as the average of all four (Average). Standard errors (where computed) are shown in parentheses. Significance codes. * $p \leq 0.05$ ** $p \leq 0.01$ *** $p \leq 0.001$

Valuation method	Coefficients	Maximum severed root diameter (mm)				Percent TPZ removed (%)			
		Fixed effects	Random effects			Fixed effects	Random effects		
			Study 1	Study 2	Study 3		Study 1	Study 2	Study 3
CTLA	Intercept	2.608 (1.563)	0.428	4.384	3.01	4.071 (0.641) ***	4.071	4.071	4.071
	Slope	-0.329 (0.084)	-4.729	-0.211	-0.302	-0.287 (0.044) *	-0.24	-0.363	-0.257
	AIC		989.521				**873.447**		
Burnley	Intercept	4.621 (2.926)	-0.175	9.377	4.662	5.032 (2.953)	0.251	10.013	4.833
	Slope	-0.270 (0.022) ***	-0.270	-0.270	-0.270	-0.290 (0.130)	-0.102	-0.532	-0.236
	AIC		901.255				**858.400**		
Helliwell	Intercept	5.045 (3.400)	0.200	10.778	4.156	4.378 (2.950)	0.096	9.626	3.411
	Slope	-0.291 (0.150)	-0.014	-0.499	-0.359	-0.384 (0.252)	-0.001	-0.853	-0.298
	AIC		979.365				974.515		
STEM	Intercept	-0.068 (2.511)	-4.677	1.071	3.403	0.075 (2.501)	-4.592	1.396	3.422
	Slope	-0.152 (0.029) *	-0.158	-0.111	-0.187	-0.145 (0.052)	-0.057	-0.225	-0.152
	AIC		777.657				**760.970**		
Average	Intercept	2.594 (1.939)	-0.54	5.704	2.62	3.046 (1.794)	0.093	6.011	3.034
	Slope	-0.256 (0.016) ***	-0.256	-0.256	-0.256	-0.272 (0.116)	-0.102	-0.492	-0.223
	AIC		810.590				**729.683**		

Valuation method	Coefficients	Total number of severed roots				$Ar_{(GL)}$			
		Fixed effects	Random effects			Fixed effects	Random effects		
			Study 1	Study 2	Study 3		Study 1	Study 2	Study 3
CTLA	Intercept	0.404 (2.148)	1.214	2.640	-2.643	0.149 (1.097)	-0.421	0.572	0.295
	Slope	-0.148 (0.091)	-0.323	-0.09	-0.032	-59.004 (17.549)	-31.280	-72.437	-73.296
	AIC		990.496				1001.079		
Burnley	Intercept	0.458 (2.832)	-1.663	5.277	-2.241	2.854 (2.653)	-1.606	7.031	3.137
	Slope	-0.073 (0.034)	-0.116	-0.085	-0.018	-70.780 (32.952)	-14.371	-123.611	-74.358
	AIC		980.904				919.428		
Helliwell	Intercept	-0.529 (1.701)	0.257	-0.169	-1.676	3.704 (2.465)	0.003	8.002	3.106
	Slope	-0.051 (0.032)	-0.017	-0.094	-0.042	-122.757 (77.965)	-0.035	-265.308	-102.929
	AIC		1082.007				**957.168**		
STEM	Intercept	-2.658 (1.750)	-5.477	-0.378	-2.118	-0.979 (2.623)	-5.624	-0.040	3.086
	Slope	-0.039 (0.021)	-0.069	-0.040	-0.009	-36.222 (15.865)	-8.137	-39.724	-60.805
	AIC		839.765				782.041		
Average	Intercept	-1.070 (1.827)	-1.560	1.576	-3.223	1.121 (1.857)	-1.982	4.414	1.207
	Slope	-0.074 (0.033)	-0.124	-0.077	-0.021	-72.043 (34.273)	-13.183	-129.263	-73.681
	AIC		921.437				824.241		

8.5 Discussion

8.5.1 Root removal and tree value

Although there was a minor deviation in the seasonal timing of root severance, negative effects of root pruning on tree growth were observed in the growing season following root loss, which agreed well with others (Watson, 1998; Ferree et al., 1999; Fini et al., 2013b; Pretzsch et al., 2016). However, treatment trees still increased in dimensions following root removal. Factors which negatively influenced the points awarded, are those relating to tree health and life expectancy. Tree vitality has been shown to be negatively affected by root removal (Watson, 1998; Benson et al., 2019b) and the trees at Tāmata Maples responded in this way, with obvious visual cues (such as premature leaf abscission and the emergence of twiggy dead material) to suggest that vitality had been compromised by the root loss. Vigour would not necessarily be affected by the root removal, since this is predetermined by genetics (Shigo, 1986a). *Q. virginiana* is a generally resilient / vigorous species (Matheny and Clark, 1998; Gilman et al., 2018) and the visual cues (canopy dieback, defoliation, leaf necrosis) to suggest that vitality had become compromised were not observed. Root pruning can also reduce the life expectancy of trees (Hauer et al., 1994), and this was particularly pertinent in the more severe root removal treatments (T4 and 3x). It could be expected that extensive root loss would shorten a tree's life span either directly, through compromised hydrological function (Barigah et al., 2013; Hember et al., 2017) and reduced carbohydrate availability (McDowell et al., 2008; Adams et al., 2009; Dickman et al., 2015), or indirectly, by predisposing it to windthrow through reduced anchorage (Smiley, 2008; Smiley et al., 2014) or the ingress of decay (Terho et al., 2007; Franklin and Larson, 2010; Peltola et al., 2017).

Minor root pruning has been shown to increase tree growth in the short-term (Watson, 1998; Dong et al., 2016), and indeed the same response was observed in the 15x treatment for the trees at PSREU (Figure 6.5). This type of response may explain why the value using the Burnley Method in this treatment group (4.62%) increased compared to controls (4.43%). The small sample size at PSREU may have positively, or negatively affected the numbers of statistical differences between treatments; most notably using the Helliwell Method.

This was a limitation at PSREU, and whilst this novel approach to assessing the effects of root pruning on mature trees was able to reveal changes in value following root loss, the PSREU results should be interpreted in acknowledgement of the effect of the small sample size.

Although the negative effects of root pruning (reduced life expectancy, reduced vitality etc.) may not be immediately obvious to assessors, these effects do still arise. Whilst there were minor differences in the seasonal timing of the root cutting, all were undertaken at the start of a period of active growth (summer). It was in the first season following root removal where the effects of root loss became most apparent. It is conceivable that the long-term effects of root loss would be alleviated over time in the lesser treatments in each study, and that the depreciating effects of root loss would eventually subside.

These findings may have practical benefits to the managers of public trees during litigation cases, or negotiations pertaining to compensatory measures for loss or damage resulting from utility trenching (Thomson and Rumsey, 1997) or pavement repair (North et al., 2017). For trees with uninterrupted root zones, it is easy to algebraically calculate a percentage of tree protection zone (TPZ) loss (Appendix B), and this independent variable performed well for each method as well as the average. Although changes to other criteria influenced the depreciation, by stratifying the scoring according to treatment, the effectiveness of the % TPZ loss would seem self-evident using CTLA, which has clearly defined criteria for assessing roots. However, root system architecture of urban trees can be restricted by infrastructure such as buildings and roads (Čermák et al., 2000), and in these cases, the circular TPZ projection would likely inaccurately reflect the tree's actual root system architecture. In these instances, one of the other continuous variables would need to be adopted. Maximum severed root diameter would seem the most appropriate choice, since it negates the need to collect and measure many small diameter roots, and also the statistical tests revealed significant slope terms for three of the five Δ value (%) responses.

8.5.2 Comparing appraisal methods

Of the four methods selected, CTLA and Burnley both use a direct mathematical operation to establish the base dollar tree value ($/area and $/volume respectively) prior to being modified based on overall tree attributes. Helliwell and STEM both adopt bands, or ranges for tree dimension, where points (and thus currency) are awarded accordingly if the tree falls within a particular range of values. The effect of using these ranges, is that it is possible for trees to move up to the next band with only very small increases in incremental growth, assuming the tree is at the upper range of the lower band of values during the first appraisal. The same small growth increases would yield only minor increases in value using CTLA, for example. This phenomenon was recorded five times at GCREC for each of the Helliwell and STEM methods, four times using Helliwell and once using STEM at PSREU. Burnley and Helliwell both adopt bands for life expectancy, although the resolution in the Burnley Method was finer than for Helliwell, allowing greater precision when awarding points in this criterion. However, range compression (very narrow bands) can make it difficult for an assessor to accurately place a tree within a particular band, and poor resolution (very wide bands) can fail to account for subtle changes. Depending on how the final dollar amount of the tree is established, and the number of points awarded, moving to the next band may have a marked effect on the final tree value. For example, STEM will award an additional six points when a tree moves up to the next band, which is then passed to a multiplicative model. The mathematical operations used in the CTLA and Burnley methods allow for a more precise resolution in the final dollar value, however this can be dramatically affected by measurement errors, since the area and volumetric calculations are exponentially proportional (Chadwick, 1975).

CTLA allows for more structured guidance when awarding points. The life expectancy and vitality criteria are replaced by a condition rating which uses several discrete units describing a range of specific tree attributes, such as root structure, and branch health. There are eight in total and focus on all aspects of the tree from roots, to fine branches and each of the strata in between. Each criterion is awarded points based on there being no problems, minor problems, major problems or extreme problems.

This type of approach allows a more focussed appraisal of the overall 'vitality' criteria included by the other methods, although still relies upon the subjective opinion of the appraiser.

There is a degree of subjectivity in any tree appraisal (Watson, 2002; Hegedüs et al., 2011) outside of direct quantitative criteria, such as mensuration. For example, points awarded in criteria such as form, life expectancy and various condition and location assessments, can vary between assessors (Tate, 1989; Abbott and Miller, 1991). Indeed, the guidance notes for each method caution, or allude to this effect. The points awarded in these types of subjective criteria are ordinally scaled. Such scales provide a rank order characterisation of attributes within which the direction of an underlying change (such as reductions in vitality) can be described, but its units of measurement cannot (Merbitz et al., 1989). There is no mathematically robust relationship between the numbers on an ordinal scale and a cardinal value derived from a mathematical operation using those numbers. This may be an inherent flaw where subjective criteria are used. Depending on the nature of the mathematical operation and the resolution of the ordinal scale, the effects of subjectivity can be magnified considerably, and two or more assessors may produce vastly dissimilar results (Watson, 2002; Ponce-Donoso et al., 2017). For example; the difference in tree value between appraisers may be as much as 125% for CTLA, 153% for Burnley, 491% for Helliwell and 86% for STEM (Watson, 2002). It is therefore conceivable that the results of this experiment may have varied, had multiple or alternate appraisers evaluated the trees, and this needs to be considered when the results are interpreted.

Furthermore, observer bias can occur when experimenters' expectations influence study outcomes. It is strongest when researchers expect a particular result and are measuring subjective variables. To minimise this bias, it is often appropriate to work 'blind', whereby experimenters are unaware of the applied treatment and thus the expected outcome (Holman et al., 2015). Whilst all identifying features of the applied treatments had been removed from the trees in this experiment, since the assessor had been privy to the treatments, it is possible that some degree of bias may have been present in the assessment.

If unintentional observer bias were present in these results, it could be expected that condition ratings of treated trees were artificially depressed. Thus, caution should be exercised in interpreting the statistical differences amongst treatments.

Another flaw with the use of ordinal scales, is vocabulary, and its subjective interpretation. For example; the nomenclature used by STEM in the "Vigour / Vitality" criterion, may not actually be representative of the tree's overall vitality. The scale jumps from "Some" to "Good" with no intermediary. It is difficult to say that a tree which has had all of its roots removed in a circumferential trench at three times its trunk diameter has "Good" vitality, but it is probably somewhere between "Some" and "Good". Similarly, at the upper end of the scale, the descriptors go from "Good", to "Very Good" and then to "Excellent". The jump from "Good" to "Very Good" would seem far less than the jump from "Some" to "Good". The CTLA and Burnley methods have an element of ordinality in their scoring systems, but endeavour to qualify in detail the particular features and attributes, to limit subjectivity and assist the assessor with logical steps to assign the most accurate score. The incremental resolution of the scale in the CTLA Method is 0.03125 (1/32) and in the Burnley method it is 0.1. Helliwell's method again endeavours to qualify / quantify the variables within each criterion, although it adopts a series of bands in several categories. The resolution in the Helliwell scale is 1. STEM adopts ordinality for six of its ten criteria and the process of awarding points relies upon the experience of the assessor. The STEM score resolution is 6.

8.6 Conclusions

The results show that root pruning negatively affected tree value across a range of treatments and treatment types in *Acer palmatum* 'Bloodgood' and *Quercus virginiana*. Tree valuation methods which use direct mathematical operations and have a fine scale resolution within a rigid framework of descriptors for awarding points (e.g. CTLA and Burnley), showed a greater sensitivity to changes in the amount of root loss. The use of bands in the awarding criteria, ordinality and poor scale resolution (very wide bands) (Helliwell and STEM) resulted in these methods showing little sensitivity to changes in the amount of root loss.

The percentage loss of TPZ proved to be the most suitable method to predict changes in value following root loss, although may not be applicable in the urban environment when root zones are interrupted by infrastructure. Maximum severed root diameter was also a good method for predicting changes in value and would be less onerous than $Ar_{(GL)}$ and total number of severed roots, which performed least well for this purpose.

These results may prove useful to the managers or owners of public or private trees, seeking compensation from utility contractors or construction workers who may have caused damage through root removal.

8.7 Epilogue

This was indeed a novel application of tree valuation methods, and one which may be useful to modern tree managers. The investigation relates to research question number 4 (How does root pruning affect tree monetary value when trees are valued using common valuation methods?) and it was seen that, with increasing root removal intensity, the value of the trees was diminished - both compared to the controls and the original value (prior to root removal).

If this were to be applied in a practical way, it would be necessary to understand the value of the tree prior to any root loss. Additionally, the method of valuation would need to be agreed upon with relevant stakeholders, since this is expected to vary geographically. The mean fit of the mixed effects models would likely be the most suitable method of application, using one of the continuous variables. In a purely practical sense – where litigation may be relevant – the level of depreciation should be agreed upon in advance within the bounds of the confidence intervals. For example; in New Zealand where STEM is the most widely used method, the range of depreciation when the maximum removed root size was 50 mm is 2.40% to 13.08% (mean fit = 7.71% depreciation), based on the 95% confidence intervals of the mean regression line.

Chapter 9: Summary of findings

9.1 Effects of root pruning treatments

Each study revealed that increasing root removal treatments yielded a greater response. Whilst it remains important to avoid making direct comparisons between species and study site - due to interspecific, climatic and site differences - it is apparent that physiology is highly dynamic, and that the responses vary considerably following root loss, often showing a temporal recovery. Understanding the different hydraulic strategies of trees ((an)isohydry) could be useful to those responsible for selecting species suitable for planting sites in urban areas. For example, isohydric species would be more vulnerable to the effects of water stress and root zone modifications than anisohydric species (Sade et al., 2012). The added physiological resilience of anisohydry may help to improve tree establishment in challenging urban locations, where soil conditions may be poor and water infiltration is less than ideal (Patterson, 1977; Kozlowski, 1999). Furthermore, the same resilience may prove to be beneficial to tree survival following root loss due to construction work in the road corridor.

9.1.1 Effects of increasing number of trenches

At each of the two New Zealand sites, the effect of increasing the number of trenches was to increase the severity of the stomatal conductance response of both *Acer* species; something which has been observed by others using different taxa (Fini et al., 2013b). Treatment effects on photochemistry were absent, perhaps because of the abundance of precipitation during the experimental period (Flexas et al., 1998), the effect of red leaf pigments in the case of *A. palmatum* (Fini et al., 2017), or the physiological plasticity of both species, enabling photorespiratory CO_2 to be recycled in the absence of severe and prolonged water stress (Takeba and Kozaki, 1998; Flexas et al., 1999).

At Tāmata Maples, the morphological responses of *Acer palmatum* 'Bloodgood' were almost uniform across the root removal treatments (T1, T2, T3 and T4), revealing reduced tree growth in comparison to controls. Although there was a general trend towards reduced growth in the *A, negundo* with increasing root removal intensity, due to the availability of trees, this particular investigation suffered from a limited number of replicates. Consequently, there were large standard errors and this may account for a reduced number of statistically significant differences (McDonald, 2014).

The overall visual assessment of tree vitality was also affected by the root removal treatments in both species, although statistically significant differences were absent. The manifestation of visual symptoms of stress is the easiest to detect in a practical sense (Pallardy, 2008). The hydraulic strategy of the two *Acer* species would suggest that prolonged stomatal closure following root loss (and thus curtailments in carbon assimilation), leads to wilting and premature leaf abscission in the growing season following root loss.

In a purely practical sense, the type of root severance to which the two *Acer* species were exposed would be uncommon in many situations. Severing roots in the way which was done at the two New Zealand sites, is likely to be encountered during tree transplanting operations, where it is necessary to sever roots on all sides of the tree prior to relocation (Pryor and Watson, 2016). The method by which roots were severed at the two New Zealand study sites was intended to achieve a wide range of $Ar_{(BH)}$ ratios. Although treatment effects were indeed recorded, since the trench offsets were prescribed at a fixed distance from the tree base (rather than as a function of trunk diameter), statistical differences between treatments and control may have been confounded somewhat by the variation in tree size within and between treatment groups; particularly the *A. negundo* at Totara Park, where the range in trunk diameters was far greater than the *A. palmatum* at Tāmata Maples. This perhaps highlights the practical importance of tree allometric relationships for best practice documents. Recommendations prescribing exclusion zones or tree offsets for work limitations, should be made as functions of trunk diameter.

9.1.2 Effects of decreasing tree protection zone radii

It was interesting to assign some empirical scrutiny to the tree protection zone guidelines which have become indoctrinated into best practice documents worldwide. Anecdotally, the use of a 12:1 tree protection zone radius may indeed be an artefact of the American imperial system of measure. A convenient 'rule of thumb' would be to prescribe one foot of tree zone protection radius for every one inch of trunk diameter (Hamilton, 1988). Irrespective of how the method was first introduced, it would seem that it is now commonplace in modern arboricultural practice when considering tree protection methods.

This investigation revealed that a circular tree protection zone which is defined by a radius equivalent to 12 times the trunk diameter at 1 m, was insufficient to avoid short-term water stress symptoms in the study trees. Although the 12x treatment did show signs of recovery from the water stress effects towards the end of the investigation, it is possible that this treatment may now be predisposed to water stress symptoms during the following summer period, or during periods of prolonged drought, which may concomitantly predispose those trees to secondary negative effects associated with biotic (Houston, 1981; Shulze, 1991; Banfield-Zanin and Leather, 2016) and abiotic (Pierre and Queiroz, 1988; Alameda et al., 2012; de Silva et al., 2012) stress.

The investigation also revealed that a circular tree protection zone which is defined by a radius equivalent to 12 times the trunk diameter at 1 m, was sufficient to avoid short-term negative effects on tree growth responses. Perhaps the application of physiological analytics to reveal the symptoms of stress is a more suitable, or robust method to reveal information which can be used to improve or prescribe tree protection guidelines.

What can be said from this investigation, is that all short-term negative effects of root removal were avoided when the radial tree protection zone offset for *Quercus virginiana* was specified using a 15:1 ratio of trunk diameter at 1 m.

9.1.3 Effects of linear root cutting

The results obtained at GCREC during the first growing season illustrated that even minor root loss through simulated utility trenching (12x treatment) was able to elicit short-term negative effects on tree physiological and morphological responses. These findings further support the results of the PSREU investigation, in that trunk offsets equivalent to 12 times the trunk diameter are insufficient to avoid short term negative effects on tree physiology (leaf water potential). In combination, the results highlight the importance of roots peripherally located within the total root system, and their role in total plant water status and water uptake.

For *Q. virginiana,* the point at which linear root cutting should be avoided lies somewhere between three and six times DBH, since only the 3x treatment showed signs of water stress 440 days after root removal. This perhaps highlights the resilience of *Q. virginiana* (Matheny and Clark, 1998; Gilman et al., 2018) as a suitable urban tree species. It is conceivable that the effects of root loss would persist for longer in a less resilient, or isohydric species, as others have seen (Watson, 1998)

It was advantageous to this study to be able to investigate the effect of the adjacent road on tree growth and physiology, both in isolation and in conjunction with the root pruning treatments. Since utility trenching in the public transport corridor is commonplace (Rogers et al., 2012), the study at GCREC using mature landscape trees was a fair approximation of a 'real world' scenario involving urban trees. Furthermore, it is the first known investigation of this nature and adds valuable information to the growing pool of knowledge on the effects of tree root severance. As with the findings of others (McPherson, 2001; Grabosky and Gilman, 2004; Celestian and Martin, 2005; Day and Amateis, 2011; Sand et al., 2018), the results of the GCREC investigation highlighted the constraints placed upon trees by hardscape and built infrastructure. These are potentially important considerations in a practical sense, when arboricultural specialists make decisions about the effects of root removal. For example, knowledge of the fact that a street tree would be less tolerant to root loss than an open-grown tree may guide decisions during the planning and implementation of physical works.

9.1.4 Effects of root pruning on tree value

The negative effects of root removal on tree growth and vitality, contemporaneously resulted in reductions in tree monetary value. Whilst the visible signs of hydraulic dysfunction and reduced vitality resulting from root severance may be absent immediately following root loss (Watson, 1998; Despot and Gerhold, 2003; Wajja-Musukwe et al., 2008; Costello et al., 2017), the appraisal methods used in this investigation incorporate criteria to examine the non-visible effects - such as reduced life expectancy, and specific characteristics of root systems. Whilst these methods may not have been developed specifically for this purpose, it was intriguing to reveal a lesser-known consequence of root loss. Although this investigation suffered from the same limitations as the others, it revealed that increasing root removal led to reductions in a tree's financial worth, one growing season after roots were removed.

The uniqueness of this investigation, the single appraiser and the limited number of treatment trees used in the analyses, may limit the ability to make broad generic statements which are applicable in all instances. However, the results were indeed enlightening and perhaps this investigation would be best delivered as a starting point for future work. Recent work on tree valuation methods has focussed on net present value (NPV), using canopy leaf area to quantify future benefits (Nowak and Aevermann, 2019). This approach has been presented as a 'proof of concept' and relies upon extrapolations of limited data in order to make preliminary yet generalised recommendations for tree compensation. Whilst the dataset may be limited, it contains neither subjective criteria nor ordinality; thereby removing these sources of variation from the results. The NPV approach may be a suitable starting point from which to develop a means to examine how root loss affects tree value. For example; an experiment could be designed which examines the effect of root loss on the NPV, i.e. by defoliation and reduced growth. The trees' NPVs could be established prior to any root removal and then examined again several months or years later following different types and intensities of root loss. Similarly, the i-Tree approach (The i-Tree Development Team, 2019) – which also uses quantitative criteria – could be adapted to suit this purpose following a similar experimental procedure. Furthermore, a long-term investigation may consider quantitatively assessing how root loss reduces life expectancy.

For example, exposing a sufficient number of replicates to various root severance treatments and contrasting their life spans with control trees would provide far greater accuracy when making estimations about future life spans in the appraisal methods. The NPV approach also relies upon life spans and mortality rates and the effects of root loss could be fed into these models.

9.2 Using root cross-sectional area ratios ($Ar_{(x)}$)

One of the initial aims of this work was to determine an 'acceptable' root pruning threshold using the allometric variable ($Ar_{(x)}$). The driving force behind this objective was predominantly due to the author's years of practical experience in the New Zealand arboricultural industry, whereby recommendations are made in relation to a maximum diameter for root severance operations. This approach inherently fails to account for the size of the tree, the total numbers of roots being removed and the distance from the tree base at which the root(s) is (are) severed.

Although significant relationships were established for one or more response variables in each experiment, it would seem however, that the way in which the experiments were designed, these relationships failed to yield sufficient information to make a generalisation about a threshold using $Ar_{(x)}$. That is; the response data for the continuous relationships were all linear in nature and no curvature was observed, precluding locating an inflection point, asymptote or the steepest part of the slope. Locating features such as this in a response where curvature is recorded, would help to reveal information relating to changes in the direction of the response, plateaus where no further change occurs, or the point at which the greatest change was recorded, respectively. It is these types of features which would point towards a threshold value of the independent variable ($Ar_{(x)}$) (Toms and Lesperance, 2003; Marshall et al., 2013). Furthermore, aside from the water potential responses, the correlations were generally weak (characterised by a low R^2), and so clearly there were other, unaccounted for variables influencing the response.

It is well accepted that roots taper and become narrower with increasing distance from the tree base (Wilson, 1964; Lyford, 1980; Coutts, 1983; Drexhage et al., 1999; Vennetier et al., 2014). Since the cross-sectional area of a circle or an ellipse is exponentially proportional to its diameter, small increases in root diameter (and thus increasing proximity to the tree) would have noticeable effects on the root's cross-sectional area. It would seem quite logical then, that at the two sites in Florida, that with increasing $Ar_{(x)}$ and $As_{(x)}$, the severity of the response increased; due to the way in which increasing $Ar_{(x)}$ and $As_{(x)}$ were achieved, i.e. by making the treatments closer to the tree. At the two New Zealand sites, values of $Ar_{(x)}$ were increased by increasing the number of trenches, and by virtue of the fact the trees varied in size (particularly at Totara Park).

The method by which roots were severed at GCREC was most likely to replicate the type of root severance occurring in an urban setting, although in this context, it is easier and more reliable to provide a trunk diameter-defined offset than any specific individual root pruning guidelines, as some of the guidance documents already do (The City of Bellevue, 2009; Fite and Smiley, 2016; Costello et al., 2017). This is also an effective and practical way to allometrically account for cumulative root loss. The large sample size of the experiment at Tāmata Maples and the way in which increasing $Ar_{(x)}$ was achieved at the New Zealand sites, made it possible for the confidence intervals of the treatment groups to be used to prescribe an $Ar_{(BH)}$ threshold, above which there would be an increased likelihood of negative effects on tree growth. This was found to be 0.22 for *Acer palmatum* 'Bloodgood' and 0.27 for *A. negundo*, corresponding to a total severed root cross-sectional area equivalent to 22% and 27% of the trunk cross sectional at 1.40 m, respectively.

The results of the GCREC investigation also highlighted that the $Ar_{(x)}$ variable only seemed to be effective in predicting short-term changes in growth and physiology following root loss. Although the water potential response remained significant in year 2, all other responses were not.

To further test the $Ar_{(x)}$ variable, and to specify more generalisable recommendations for its use, experiments would need to be conducted which increased $Ar_{(x)}$ in different ways, i.e. more roots, larger roots, different proximities to the tree base, and not necessarily within a single (or multiple) trench(s) - mimicking perhaps localised excavations to repair buried utilities or installing street furniture such as lighting structures. These different effects could then be contrasted to examine how the response data were affected. For example; contrast the responses of trees which have received $Ar_{(x)}$ root pruning ratios of 0.75 by removing two or three large roots with those receiving the same $Ar_{(x)}$ ratio achieved by removing several hundred small roots. The investigations would need to be carried out over several years with a range of species, and also take account of ongoing microvariations in the $Ar_{(x)}$ ratios due to increasing trunk diameters and new root growth. The use of mini-rhizotrons and / or destructive sampling of a subset of the sample population would be necessary for the latter.

Furthermore, it is conceivable that $Ar_{(x)}$ thresholds would vary between species and age due to differences in root system morphology (Bond-Lamberty et al., 2002; Nielsen and Hansen, 2006). Comparing the mean $Ar_{(x)}$ values of the T4 treatment at Tāmata Maples (0.83) with those of the 3x treatment at PSREU (0.52) illustrates this effect. The mean trunk diameter offset of trenches made with *A. palmatum* at Tāmata Maples was 4.20 times DBH ($\delta = 0.98$), yet the $Ar_{(x)}$ ratio was 1.59 times greater than that of *Q. virginiana,* when roots were severed on all sides at 3 times trunk diameter. The differences in $Ar_{(x)}$ ratios could be due to species (Nielsen and Hansen, 2006), site characteristics (Szota et al., 2007; Danjon et al., 2008), age class (Ganatsas and Spanos, 2005) or production methods / planting technique (Gilman et al., 2016a).

In a purely practical sense, the use of $Ar_{(x)}$ may not be immediately viable, since to make accurate use of it, all woody roots measuring 2 mm or more in diameter would need to be measured and accounted for. This would indeed be a cumbersome task in a commercial environment. Whilst there are inherent flaws in using a maximum root diameter threshold, this may be a useful starting point from which to include other variables (such as trunk diameter, total number of severed roots, mean root diameter and distance from the tree base (as a function of trunk diameter)) into predictive models.

9.3 Experimental limitations and the implications thereof

It is pertinent here to again acknowledge the limitations of these investigations. Those being a short duration (particularly in the case of Tāmata Maples, Totara Park and PSREU) and a low number of replicates (in the case of Totara Park and PSREU). These limitations were unfortunate consequences of the logistical constraints of the experiments outlined in section 3.4.

9.3.1 Temporal limitations

Whilst several significant relationships were recorded between treatment (root pruning) and response (tree growth, physiology and monetary value) in the growing seasons after root loss, it was noted at each study site, that trees showed a general trend towards physiological recovery over time. By visiting the GCREC trees in 2018, the magnitude of the temporal recovery after one year was observed, whereby all trees had regained normal growth and only the 3x treatment exhibited signs of water stress. This kind of temporal recovery has been seen by others using different genera (Watson, 1998; Fini et al., 2013b). In the specific instance of GCREC, the conclusions drawn in relation to making recommendations for updating current practice, were based on the temporal recovery of the 6x and 12x trees. It may be that the 3x treatment will, or indeed has recovered from the effects of root loss as these relate to water stress, and indeed the trees at PSREU would be expected to exhibit a similar behaviour, thus enabling a more informed recommendation as this relates to minimum tree protection zone radii. Furthermore, whilst there was evidence of recovery in the 6x and 12x treatments at GCREC, it may be that these treatments would show signs of stress during periods of less favourable growing conditions (e.g. drought). Trees which have not adequately restored the root to shoot ratio are likely more predisposed to the re-emergence of water stress symptoms, when water becomes limiting. Thus, it may be that the 6x treatment was sufficiently compromised such that the recommendation would be amended to reflect a greater trenching offset, had this type of response been observed. A longer study duration may reveal these effects, and this is true of each investigation reported in this thesis.

Ideally, all the trees involved in these investigations would be monitored for three to five years, however this was simply not possible due largely to logistical constraints, trees being removed and academic timelines.

Conversely, it is conceivable that there may be a temporal delay in the growth responses based upon the way in which trees store and allocate carbohydrate resources. In addition to playing a key role in maintaining respiration, carbohydrate reserves (often stored in the woody tissues near the tree base (Coutts, 1987; Hartmann and Trumbore, 2016; Ramírez-Briones et al., 2017)) are mobilised for early-season growth of leaves, reproductive structures, stems and shoots (Kozlowski, 1991). Mobilising stored carbohydrates safeguards against any asynchrony of supply and demand which may occur over temporal (e.g. a deciduous tree in spring is unable to fix atmospheric carbon until it has made assimilative structures) or spatial (e.g. across plant organs) scales (Hartmann and Trumbore, 2016). In temperate regions, evergreen species are able to accumulate carbohydrates much later into the winter (Kozlowski, 1991), and so there is a good likelihood that the *Q. virginiana* at both Floridian sites had ample quantities of accumulated carbohydrate reserves from the previous season(s), to sustain trunk diameter growth in all but the most severe treatment (3x at PSREU). The short temporal nature of all the experiments may have precluded recording any noticeable change in trunk diameter growth in some treatments, which were able to continue using stored carbohydrate reserves. A longer experimental duration may have revealed changes in trunk diameter growth emerging over time as carbohydrate reserves were depleted.

9.3.2 Statistical limitations

The number of replicates is important when interpreting statistically significant differences. In biology, there is heterogeneity in the responses between individuals. Replication increases the reliability of parameter estimates, and enables us to quantify the variability (variance and standard errors) found within the same treatment (Crawley, 2015). Standard errors can be unrepresentatively large with too few replicates (McDonald, 2014), and so replication improves the statistical power of the experiment and reduces the likelihood of Type II errors (the analysis fails to reject the null hypothesis, when an effect is truly present).

Conversely, too few replicates may also produce Type I errors (the analysis rejects the null hypothesis, when a true effect is in fact absent), leading to ambiguous conclusions which may not be revealed if the experiment is repeated (Lemoine et al., 2016).

Both Totara Park (*A. negundo*) and PSREU (*Q. virginiana*) suffered from a small sample size and thus a small number of replicates. The numbers of *A. palmatum* at Tāmata Maples were sufficient to ensure an adequate number of replicates (20), and so the conclusions drawn from the experimental findings can be considered as robust (within the temporal limitations previously described). *A. negundo* responses showed larger standard errors across the range of treatments, likely due to low replications (4). It is quite likely that with the same, or similar number of *A. negundo* replicates (20), more differences would have been found and greater certainties could be gained about how these two species responded to root loss.

The same is true of the live oak at PSREU ($n = 3$), where the standard errors of the responses were, in most cases, quite large. The purpose was to test a range of tree protection zone radii with the available resources. Decreasing the number of treatments would have increased the number of replicates but limited the resolution. That is; for $n = 3$, treatments = 6, allowing for small incremental changes between treatments (multiples of trunk diameter of the order three). For $n = 6$, treatments = 3, precluding the small increments between treatments, and potentially not revealing the specific location where significant differences between treatment and control emerged, but improving the statistical power of the experiment. This was an unfortunate trade off with the small sample size. Ideally, this study would have used 60 (or more) trees allowing for $n = 10$ with 6 treatments, providing greater certainty of the conclusions.

Generalisability relates to the adequacy with which the results from one sample of observations from a single population can be used to make generalised inferences about that population (Matt and Sklar, 2015). It is therefore important to consider the different environmental regimes of trees and plants, to avoid generalising the results of a single sample to a population scale, if a sufficient understanding of the responses of trees and plants to different types of stress (e.g. construction impacts, root loss and other abiotic influence) is to be achieved (Mooney et al., 1991). This research was limited by the availability of trees and resources, and so the results are unlikely to be broadly generalisable on a population scale (e.g. to all biomes). One way to make more broadly generalisable results would be to experiment upon several representative samples (e.g. the most commonly used urban tree species) from multiple populations. For example, several samples of mesic, xeric and hydric tree species (Day et al., 2001), or samples of trees with different types of root architecture (e.g. sinker, heart or tap root systems) (Pretzsch et al., 2016). This would avoid the need to experiment on every tree species and add some degree of robustness when making generalised recommendations relating to tree care based on their biological responses to abiotic stress.

9.4 Implications and applications of this research

There are practical benefits to this work, which are implementable in the day-to-day undertakings of arboricultural practitioners responsible for managing works affecting tree root zones. More importantly, the findings are of great value to those responsible for the planning and preparation of such work.

It is hoped that the research outputs which have been disseminated in written and oral form, will precipitate into future best management practice guidelines relating to root care and root care practices. For example, the work of Smiley (2008) - which recommends that linear root cutting (trenching) should not be undertaken at distances closer than three times the trunk diameter to the tree base to avoid stability loss – has since been included in the American National Standards Institute (ANSI) standard in relation to tree root protection (ANSI 300: Part 5) (Fite and Smiley, 2016).

The results of the utility trenching experiment at GCREC suggest that trenching closer to the tree than six times DBH (equivalent to 24.10% TPZ removal assuming a tree protection radius of 15 times DBH), is likely to result in sustained water stress symptoms, supporting recent assertive guidelines about trenching offsets and negative health effects (Costello et al., 2017). The new information provided by this research would be a suitable supplement to existing recommendations, adding empirical robustness to the guidelines. Furthermore, the findings should hopefully furnish arboricultural experts with a robust platform on which to argue that tree protection zone radii should be prescribed using a 15:1 ratio of trunk diameter. Whilst experiments would need to be undertaken using a range of species for extended durations to make the arguments robust, this first look at empirically testing the TPZ principle highlights the importance of roots peripherally located within the total root system.

With specific regard to the Australian Standard (AS4970 - 2009: Protection of trees on development sites) - which recommends that TPZ encroachments should not exceed 10% - the guidelines provided in this document in relation to TPZ incursions are indeed robust but could be 'relaxed' somewhat in light of these findings. The purpose of tree protection mechanisms by their very nature is to enable a juxtaposition of trees and infrastructure. Thus, by increasing the incursion threshold to 20% (assuming a TPZ radius of 15 times DBH), developmental constraints imposed by existing trees could be reduced, whilst still minimising long-term effects on tree health. The use of irrigation following root loss would be actively encouraged, to alleviate the effects of root loss-induced water stress and limit negative effects during periods of abnormal or irregular water shortage relative to usual conditions (drought), or when water is likely to become a limiting resource (e.g. during summer, or if other factors such as new impermeable surfaces limit infiltration).

The findings of the valuation investigation were indeed revealing and may be useful to urban tree managers. Policy documents could be established within local jurisdictions, or specifications written into contracts for work in the public domain. With a benchmark for the devaluing effects of root loss, these figures could be used as bonds or penalties, serving more as a financial deterrent to those undertaking work around public or highly valued trees than any source of revenue.

9.5 Conclusions

By exposing three different species of tree, in different geographic ranges, to different types and intensities of root removal treatment, and contrasting their responses with control trees, this work has determined that increasing root removal treatments are negatively correlated with tree physiological and morphological responses, as well as tree monetary value. The results observed in relation to the physiological and morphological responses agree well with those observed by others.

Whilst one of the initial goals - or rather, aspirations - of this work was to investigate whether the $Ar_{(x)}$ variable was capable of being used in way to prescribe a root pruning threshold, it was evident that this was not the case within the constructs of the experimental designs and what was subsequently learned about tree responses to root loss. Whilst the practice of root pruning will undoubtedly continue as the urban environment undergoes continued modification, it may be, at this time, that arboricultural practitioners will need to continue to rely on experience and more generalised guidance on root pruning thresholds to account for cumulative root loss (for example; trunk diameter trenching offsets).

What was ascertained in relation to the trenching treatments, however, is of great value to arboricultural practitioners and those responsible for the development of best practice documents, local authority regulations and statutes. Furthermore, the findings complement what is currently known about root loss due to utility trenching and tree stability and support recent assertions about trunk diameter-defined offsets and negative health effects.

In conclusion, arboricultural practitioners should continue to exercise care when making decisions about removing roots. It is evident that trees respond differently between species and age classes and so broad generalisations are difficult to make. Engineers and utility contractors should be encouraged to devise alternatives to traditional methods which may align with immediate budgetary constraints but could have long-term environmental or financial consequences to the urban forest and the managers thereof.

Quod erat demonstrandum

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Appendix A: Chapter 7 results tables

Table A 1: Model coefficients, statistical significance and AIC values for pre-dawn leaf water potential (Ψ (MPa)) response following root severance. Coefficient standard errors are shown in parentheses. Significance codes. * $p \leq 0.05$ ** $p \leq 0.01$ *** $p \leq 0.001$

Coefficient	**Days since root severance**					
	30	**45**	**62**	**70**	**102**	**440**
Intercept	-0.35 (0.02) ***	0.00 (0.13)	-0.38 (0.02) ***	-0.30 (0.02) ***	-0.30 (0.02) ***	-0.34 (0.02) ***
12x	-0.02(0.03)	-0.08 (0.04) *	-0.02 (0.02)	-0.04 (0.03)	-0.08 (0.02) **	-0.03 (0.02)
6x	-0.01 (0.03)	-0.11 (0.07) **	-0.03 (0.02)	-0.06 (0.25) *	-0.10 (0.20) ***	-0.01 (0.02)
3x	-0.08 (0.03) *	-0.20 (0.04) ***	-0.09 (0.02) ***	-0.12 (0.03) ***	-0.23 (0.20) ***	-0.07 (0.02) **
DBH						
Road_D						
Road_D : DBH						
θ		-0.01 (0.01) *				
12x : θ						
6x : θ						
3x : θ						
R^2	0.33	0.57	0.43	0.47	0.79	0.36
p value	0.013	<0.001	0.002	<0.001	<0.001	0.008
AIC	-84.73	-73.43	-104.63	-95.46	-99.15	-104.45

Table A 2: Model coefficients, statistical significance and AIC values for maximum PSII photochemical efficiency (Fv/Fm) response following root severance. Coefficient standard errors are shown in parentheses. Significance codes. * p≤0.05 ** p≤0.01 *** p≤0.001

Coefficient	**Days since root severance**					
	30	**45**	**62**	**70**	**102**	**440**
Intercept	0.82 (0.01) ***	0.79 (0.01) ***	0.79 (0.00) ***	0.72 (0.26) ***	0.80 (0.00) ***	0.78 (0.00) ***
12x		-0.01 (0.00)				
6x		-0.01 (0.00) *				
3x		-0.02 (0.00) ***				
DBH						
Road_D	0.00 (0.00) *	-0.00 (0.00) ***				
Road_D : DBH						
θ	-0.01 (0.00) ***	0.00 (0.00) **		0.00 (0.00) **		
12x :θ						
6x : θ						
3x : θ						
R^2	0.49	0.73		0.21		
p value	<0.001	<0.001	<0.001	0.009	<0.001	<0.001
AIC	-188.54	-211.17	-196.27	-163.50	-192.82	-180.76

Table A 3: Model coefficients, statistical significance and AIC values for variable minimum fluorescence (Fv/Fo) response following root severance. Coefficient standard errors are shown in parentheses. Significance codes. * p≤0.05 ** p≤0.01 *** p≤0.001

Coefficient	**Days since root severance**					
	30	**45**	**62**	**70**	**102**	**440**
Intercept	4.60 (0.15) ***	4.05 (0.54) ***	3.66 (0.04) ***	2.29 (0.46) ***	4.06 (0.05) ***	3.61 (0.05) ***
12x		-0.27 (0.15)		-0.40 (0.15) *		
6x		-0.47 (0.16) **		-0.22 (0.15)		
3x		-0.70 (0.15) ***		-0.37 (0.15) *		
DBH						
Road_D	0.03 (0.02) *	-0.05 (0.01) **				
Road_D : DBH						
θ	-0.11 (0.02) ***	0.06 (0.03) *		0.11 (0.05) ***		
12x :θ						
6x : θ						
3x : θ						
R^2	0.43	0.63		0.44		
p value	<0.001	<0.001	<0.001	0.004	<0.001	<0.001
AIC	13.34	16.10	-6.42	15.54	4.51	7.15

Table A 4: Model coefficients, statistical significance and AIC values for stomatal conductance (g_s (m mol m^{-2} s^{-1})) response following root severance. Coefficient standard errors are shown in parentheses. Significance codes. * p≤0.05 ** p≤0.01 *** p≤0.001

Coefficient	**Days since root severance**					
	30	**45**	**62**	**70**	**102**	**440**
Intercept	210.42 (12.49) ***	219.17 (17.51) ***	398.90 (73.46) ***	435.84 (77.65) ***	200.64 (46.54) ***	271.21 (6.46) ***
12x						
6x						
3x						
DBH					1.92 (0.93) *	
Road_D		-6.53 (2.22) **				
Road_D : DBH						
θ			-7.82 (3.58) *	-11.17 (4.58) *	-4.64 (1.70) *	
12x :θ						
6x : θ						
3x : θ						
R^2		0.23	0.14	0.17	0.3	
p value	<0.001	0.006	0.037	0.021	0.007	<0.001
AIC	353.97	330.85	304.67	331.83	294.00	313.07

Table A 5: Model coefficients, statistical significance and AIC values for leaf temperature (°C) response following root severance. Coefficient standard errors are shown in parentheses. Significance codes. * p≤0.05 ** p≤0.01 *** p≤0.001

Coefficient	**Days since root severance**					
	30	**45**	**62**	**70**	**102**	**440**
Intercept	25.10 (2.28) ***	34.67 (0.26) ***	37.23 (0.92) ***	33.99 (0.201 ***	33.72 (0.63) ***	22.90 (6.12) **
12x						16.59 (6.86) *
6x						4.40 (7.00)
3x						5.19 (6.57)
DBH	0.12 (0.07)					0.10 (0.05)
Road_D	0.84 (0.37) *	-0.14 (0.03) ***		-0.12 (0.03) ***		0.63 (0.30)
Road_D : DBH	-0.02 (0.01) *					-0.02 (0.01) *
θ	0.35 (0.08) ***		-0.23 (0.05) ***		-0.11 (0.03) **	0.31 (0.25)
12x :θ						-0.74 (0.03) *
6x : θ						-0.19 (0.32)
3x : θ						-0.23 (0.30)
R^2	0.57	0.37	0.49	0.43	0.27	0.42
p value	<0.001	<0.001	<0.001	<0.001	0.003	0.2384
AIC	89.03	70.79	32.76	56.05	47.412	72.37

Table A 6: Model coefficients, statistical significance and AIC values for pre-dawn leaf water potential (Ψ (MPa)) response following root severance using $Ar_{(BH)}$ and $As_{(BH)}$ as the explanatory variables. Coefficient standard errors are shown in parentheses. Significance codes. * p≤0.05 ** p≤0.01 *** p≤0.001

Variable	Coefficient	Days since root severance						
		30	**45**	**62**	**70**	**102**	**2017 Mean**	**440**
$Ar_{(BH)}$	Intercept	-0.34 (0.02) ***	-0.27 (0.02) ***	-0.38 (0.01) ***	-0.31 (0.01) ***	-0.33 (0.01) ***	-0.33 (0.01) ***	-0.34 (0.01) ***
	$Ar_{(BH)}$	-0.37 (0.13) **	-0.89 (0.13) ***	-0.38 (0.09) ***	-0.51 (0.10) ***	-0.934 (0.12) ***	-0.55 (0.06) ***	-0.31 (0.09) **
	DBH							
	Road_D							
	Road_D : DBH							
	θ							
	$Ar_{(BH)}$: θ							
	R^2	0.23	0.61	0.37	0.47	0.69	0.75	0.32
	p value	0.007	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.001
	AIC	-84.49	-82.62	-105.53	-99.86	-91.12	-123.99	-106.26
$As_{(BH)}$	Intercept	-0.35 (0.02) ***	-0.24 (0.03) ***	-0.38 (0.01) ***	-0.31 (0.01) ***	-0.34 (0.01) ***	-0.34 (0.01) ***	-0.32 (0.02) ***
	$As_{(BH)}$	-0.10 (0.05) *	-0.35 (0.05) ***	-0.14 (0.04) ***	-0.22 (0.03) ***	-0.34 (0.05) ***	-0.20 (0.02) ***	-0.14 (0.03) ***
	DBH							
	Road_D		-0.01 (0.00) *					-0.00 (0.00) *
	Road_D : DBH							
	θ							
	$As_{(BH)}$: θ							
	R^2	0.14	0.66	0.35	0.60	0.65	0.74	0.44
	p value	0.046	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	<0.001
	AIC	-79.77	-81.92	-100.86	-103.93	-83.44	-119.00	-105.38

Table A 7: Model coefficients, statistical significance and AIC values for maximum PSII photochemical efficiency (Fv/Fm) response following root severance using $Ar_{(BH)}$ and $As_{(BH)}$ as the explanatory variables. Coefficient standard errors are shown in parentheses. Significance codes. * p≤0.05 ** p≤0.01 *** p≤0.001

Variable	Coefficient	Days since root severance						
		30	**45**	**62**	**70**	**102**	**2017 Mean**	**440**
$Ar_{(BH)}$	Intercept	0.83 (0.01) ***	0.78 (0.01) ***	0.78 (0.00) ***	0.72 (0.03) ***	0.79 (0.01) ***	0.80 (0.00) ***	0.79 (0.00) ***
	$Ar_{(BH)}$		-0.08 (0.02) ***			-0.59 (0.27) *	-0.04 (0.02) *	
	DBH							
	Road_D	0.00 (0.00) *	-0.00 (0.00)***					
	Road_D : DBH							
	θ	-0.00 (0.00) ***	0.00 (0.00) **		0.00 (0.00) **	0.00 (0.00)		
	$Ar_{(BH)}$: θ					0.03 (0.01) *		
	R^2	0.49	0.62		0.21	0.24	0.14	
	p value	<0.001	<0.001	<0.001	0.009	0.053	0.037	<0.001
	AIC	-188.54	-204.34	-196.24	-163.50	-195.50	-212.53	-158.08
$As_{(BH)}$	Intercept	0.82 (0.01) ***	0.82 (0.03) ***	0.78 (0.00) ***	0.72 (0.03) ***	0.79 (0.01) ***	0.80 (0.00) ***	0.79 (0.00) ***
	$As_{(BH)}$		-0.02 (0.01) *			-0.23 (0.10) *	-0.01 (0.01) *	
	DBH		-0.00 (0.00) *					
	Road_D		-0.00 (0.00) **					
	Road_D : DBH							
	θ	-0.00 (0.00) ***	0.00 (0.00) *		0.00 (0.00) **	0.00 (0.00)		
	$As_{(BH)}$: θ					0.01 (0.01) *		
	R^2	0.40	0.57		0.22	0.34	0.14	
	p value	<0.001	0.002	<0.001	0.009	0.011	0.040	<0.001
	AIC	-185.01	-151.12	-196.27	-163.50	-192.11	-204.51	-118.84

Table A 8: Model coefficients, statistical significance and AIC values for maximum PSII photochemical efficiency (Fv/Fo) response following root severance using $Ar_{(BH)}$ and $As_{(BH)}$ as the explanatory variables. Coefficient standard errors are shown in parentheses. Significance codes. * p≤0.05 ** p≤0.01 *** p≤0.001

Variable	Coefficient	Days since root severance						
		30	**45**	**62**	**70**	**102**	**2017 Mean**	**440**
$Ar_{(BH)}$	Intercept	4.60 (0.15) ***	3.31 (0.51) ***	3.66 (0.04) ***	2.23 (0.50) ***	4.06 (0.05) ***	4.11 (0.05) ***	3.66 (0.05) ***
	$Ar_{(BH)}$		-2.44 (0.67) **				-0.93 (0.40) *	
	DBH							
	Road_D	0.03 (0.02) *	-0.05 (0.02) **					
	Road_D : DBH							
	θ	-0.12 (0.02) ***	0.09 (0.03) **		0.09 (0.03) **			
	$Ar_{(BH)}$: θ							
	R^2	0.43	0.51		0.24		0.16	
	p value	< 0.001	< 0.001	< 0.001	0.005	< 0.001	0.026	< 0.001
	AIC	13.34	20.60	-6.42	18.91	4.51	-14.86	7.15
$As_{(BH)}$	Intercept	4.60 (0.15) ***	3.26 (0.54) ***	3.63 (0.04) ***	2.03 (0.49) ***	4.06 (0.05) ***	4.12 (0.05) ***	3.66 (0.05) ***
	$As_{(BH)}$		-0.82 (0.28) **		-0.54 (0.25) *		-0.35 (0.15) *	
	DBH							
	Road_D	0.03 (0.02) *	-0.06 (0.02) **					
	Road_D : DBH							
	θ	-0.11 (0.02) ***	0.09 (0.03) **		0.11 (0.03) ***			
	$As_{(BH)}$: θ							
	R^2	0.43	0.46		0.37		0.16	
	p value	< 0.001	0.001	< 0.001	0.002	< 0.001	0.029	< 0.001
	AIC	13.34	24.10	-6.42	16.07	4.51	-13.24	7.15

Table A 9: Model coefficients, statistical significance and AIC values for stomatal conductance (g_s (m mol m^{-2} s^{-1})) response following root severance using $Ar_{(BH)}$ and $As_{(BH)}$ as the explanatory variables. Coefficient standard errors are shown in parentheses. Significance codes. * p≤0.05 ** p≤0.01 *** p≤0.001

Variable	Coefficient	Days since root severance						
		30	**45**	**62**	**70**	**102**	**2017 Mean**	**440**
$Ar_{(BH)}$	Intercept	276.52 (23.73) ***	294.13 (20.22) ***	432.32 (79.99) ***	247.56 (10.69) ***	235.176 (49.32) ***	436.35 (71.88) ***	269.08 (7.49) ***
	$Ar_{(BH)}$					-144.90 (61.11) *		
	DBH					2.16 (1.03) *		
	Road_D	-9.23 (2.98) **	-7.47 (2.54) **					
	Road_D : DBH							
	θ			-9.66 (3.93) *		-6.18 (1.77) **	-11.90 (4.14) **	
	$Ar_{(BH)}$: θ							
	R^2	0.3	0.28	0.22		0.51	0.27	
	p value	0.005	0.007	0.022	<0.001	0.002	0.009	< 0.001
	AIC	266.68	259.00	237.21	261.10	224.90	233.50	244.01
$As_{(BH)}$	Intercept	210.42 (12.49) ***	276.52 (23.73) ***	432.32 (79.99) ***	247.560 (10.69) ***	291.00 (39.04) ***	436.35 (71.88) ***	269.08 (7.49) ***
	$As_{(BH)}$							
	DBH							
	Road_D		-9.23 (2.96) **				-11.90 (4.14) **	
	Road_D : DBH							
	θ			-9.66 (3.93) *		-6.06 (2.04) **		
	$As_{(BH)}$: θ							
	R^2		0.30	0.22		0.89	0.27	
	p value	< 0.001	0.005	0.022	<0.001	0.007	0.008	< 0.001
	AIC	353.94	266.68	237.21	261.10	230.29	233.50	244.01

Table A 10: Model coefficients, statistical significance and AIC values for leaf temperature (°C) response following root severance using $Ar_{(BH)}$ and $As_{(BH)}$ as the explanatory variables. Coefficient standard errors are shown in parentheses. Significance codes. * p≤0.05 ** p≤0.01 *** p≤0.001

Variable	Coefficient	Days since root severance						
		30	**45**	**62**	**70**	**102**	**2017 Mean**	**440**
$Ar_{(BH)}$	Intercept	25.11 (2.28) ***	34.61 (0.26) ***	37.268 (0.92) ***	33.99 (0.21) ***	33.72 (0.63) ***	33.00 (0.15) ***	33.17 (0.13) ***
	$Ar_{(BH)}$							
	DBH	0.12 (0.07)						
	Road_D	0.84 (0.37) *	-0.14 (0.03) ***		-0.12 (0.03) ***		-0.05 (0.02) **	
	Road_D : DBH	-0.03 (0.01) *						
	θ	0.35 (0.08) ***		-0.23 (0.05) ***		-0.11 (0.03) **		
	$Ar_{(BH)}$: θ							
	R^2	0.56	0.37	0.49	0.43	0.27	0.22	
	p value	< 0.001	<0.001	< 0.001	< 0.001	0.00	0.008	< 0.001
	AIC	89.03	70.79	32.76	56.05	47.41	34.77	69.08
$As_{(BH)}$	Intercept	25.11 (2.28) ***	34.67 (0.26) ***	37.27 (0.92) ***	33.99 (0.21) ***	33.72 (0.63) ***	33.00 (0.15) ***	33.17 (0.13) ***
	$As_{(BH)}$							
	DBH	0.12 (0.08)						
	Road_D	0.84 (0.37) *	-0.14 (0.03) ***		-0.12 (0.03) ***		-0.05 (0.02) **	
	Road_D : DBH	-0.025 (0.011) *						
	θ	0.35 (0.08) ***		-0.23 (0.05) ***		-0.11 (0.03) **		
	$As_{(BH)}$: θ							
	R^2	0.56	0.37	0.49	0.43	0.27	0.22	
	p value	< 0.001	<0.001	< 0.001	< 0.001	0.00	0.008	< 0.001
	AIC	89.03	70.79	32.76	56.05	47.41	34.77	69.08

Table A 11: Model coefficients, statistical significance and AIC values for trunk diameter increase (Ø (cm)), shoot extension (mm) and leaf area (cm^2) responses for each treatment following root removal. Coefficient standard errors are shown in parentheses. Significance codes. * p≤0.05 ** p≤0.01 *** p≤0.001

	2017			2018		
Coefficient	**Response**			**Response**		
	Ø (cm)	**Shoot extension (mm)**	**Leaf area (cm^2)**	**Ø (cm)**	**Shoot extension (mm)**	**Leaf area (cm^2)**
Intercept	1.17 (0.121) ***	396.31 (28.24) ***	8.43 (0.43) ***	0.40 (0.59)	315.90 (11.60) ***	2.69 (0.11) ***
12x		-97.29 (38.66) *	-2.17 (0.59) ***			
6x		-146.13 (38.67) ***	-2.72 (0.59) ***			
3x		-132.24 (38.66) **	-2.92 (0.59) ***			
DBH				0.08 (0.02) ***		
Road_D	0.03 (0.02) *					
Road_D : DBH						
θ						
12x : θ						
6x : θ						
3x : θ						
R^2	0.13	0.39	0.53	0.40		
p value	0.048	0.004	<0.001	<0.001	<0.001	<0.001
AIC	22.43	361.13	101.54	42.11	349.37	59.39

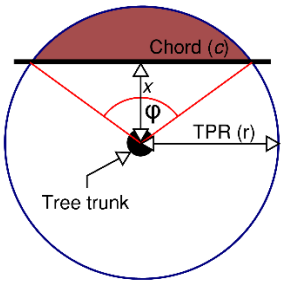
Table A 12: Model coefficients, statistical significance and AIC values for trunk diameter increase (Ø (cm)), shoot extension (mm) and leaf area (cm^2) responses using *Ar(BH)* and *As(BH)* as the explanatory variables . Coefficient standard errors are shown in parentheses. Significance codes. * p≤0.05 ** p≤0.01 *** p≤0.001

		2017			2018		
Variable	**Coefficient**	**Response**			**Response**		
		Ø (cm)	**Shoot extension (mm)**	**Leaf area (cm^2)**	**Ø (cm)**	**Shoot extension (mm)**	**Leaf area (cm^2)**
Ar (BH)	Intercept	-0.20 (0.79)	337.70 (21.20) ***	7.18 (0.35) ***	0.40 (0.59)	337.70 (21.20) ***	2.69 (0.11) ***
	Ar (BH)	17.33 (8.15) *	-469.50 (184.00) *	-9.38 (3.07) **		-312.30 (130.01) *	
	DBH				0.08 (0.02) ***		
	Road_D					-6.00 (2.77) *	
	Road_D : DBH						
	θ	0.10 (0.05) *					
	Ar(BH) : θ	-1.09 (0.49) *					
	R^2	0.21	0.18	0.24	0.40	0.24	
	p value	0.098	0.016	0.005	<0.001	0.020	<0.001
	AIC	23.56	366.02	112.24	44.89	344.67	59.39
As (BH)	Intercept	0.21 (0.71)	337.31 (19.08) ***	6.95 (0.37) ***	0.40 (0.59)	379.21 (25.40) ***	2.69 (0.11) ***
	As (BH)	5.07 (2.28) *	-210.37 (64.36) **	-2.67 (1.26) *		-122.69 (48.34) *	
	DBH	0.02 (0.01) *			0.08 (0.02) ***		
	Road_D	0.04 (0.04) **				-6.02 (2.74) *	
	Road_D : DBH						
	θ	0.01 (0.04)					
	As(BH) : θ	-0.31 (0.14) *					
	R^2	0.51	0.28	0.14	0.40	0.26	
	p value	0.003	0.003	0.043	<0.001	0.020	<0.001
	AIC	6.19	349.60	113.71	44.89	331.84	59.39

Appendix B: Geometric calculations and TPZ Equations

The following diagrams and equations describe the various mathematical operations used to calculate the percentage loss of tree protection zone for each treatment type. In each diagram, the outer circle represents the extent of the TPZ, and the shaded regions represent the removed TPZ portions.

Tāmata Maples

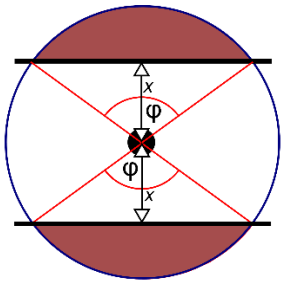


Treatment T1

$$Area\ of\ the\ segment = \left((\pi r^2) \times \frac{\varphi}{360}\right) - \left(x \times \sqrt{(r^2 - x^2)}\right) \quad \text{(Equation B 1)}$$

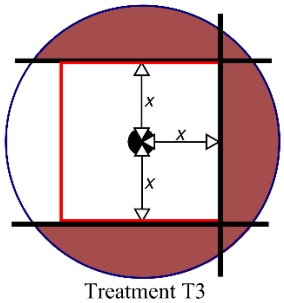
$$Percent\ TPZ\ loss = \frac{Area\ of\ the\ segment}{\pi r^2} \times 100 \quad \text{(Equation B 2)}$$

Where: φ = the angle subtended at the centre of the tree trunk by two radii (r) which meet the chord (c) (the trench) where it intersects the TPZ circumference.



Treatment T2

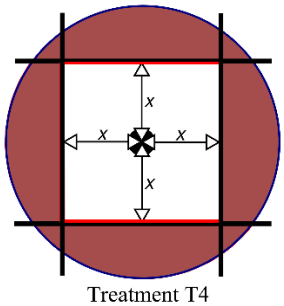
$$Percent\ TPZ\ loss = \frac{2\ (Area\ of\ a\ single\ segment)}{\pi r^2} \times 100 \quad \text{(Equation B 3)}$$



Treatment T3

$$Percent\ TPZ\ loss = \left(\frac{\left(2(AS) + \left(\frac{\pi r^2 - 2(AS) - (2x)^2}{2}\right)\right)}{\pi r^2}\right) \times 100 \quad \text{(Equation B 4)}$$

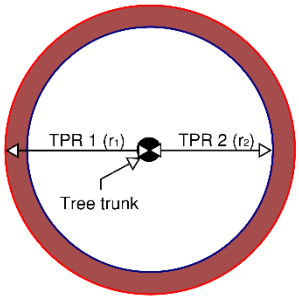
Where: AS = Area of a single segment (refer treatments T1 and T2)



Treatment T4

$$Percent\ TPZ\ loss = \frac{(\pi r^2 - (2x)^2)}{\pi r^2} \times 100 \quad \text{(Equation B 5)}$$

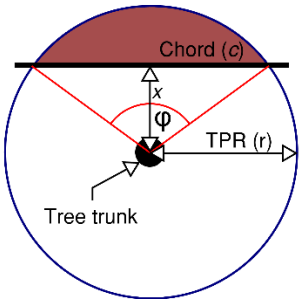
Plant Science Research and Education Unit



$$Percent\ TPZ\ loss = \frac{\pi {r_1}^2 - \pi {r_2}^2}{\pi {r_1}^2} \times 100$$ (Equation B 6)

Where: r_1 = the TPZ radius equivalent to 15 times DBH and r_2 = the treatment TPZ radius, i.e. 12, 9, 6 or 3 times DBH

Gulf Coast Research and Education Centre



$$Area\ of\ the\ segment = \left((\pi r^2) \times \frac{\varphi}{360}\right) - \left(x \times \sqrt{(r^2 - x^2)}\right)$$ (Equation B 7)

$$Percent\ TPZ\ loss = \frac{Area\ of\ the\ segment}{\pi r^2} \times 100$$ (Equation B 8)

Where: φ = the angle subtended at the centre of the tree trunk by two radii (r) which meet the chord (c) (the trench) where it intersects the TPZ circumference

Appendix C: ERT sapwood area R code

A comprehensive R code sequence which extracts the resistivity data from the PiCUS ERT output file and computes sapwood area can be downloaded from the following URLs:

R Studio file (.R)

https://www.dropbox.com/s/si0xv1aeetn0z4w/ERT_SW_BDY_LOCATION_SEQUENCE_VX03.R?dl=0

MS Word version (.docx)

https://www.dropbox.com/s/4tcbxuv83tqrdnw/ERT_SW_BDY_LOCATION_SEQUENCE%5BVX002%5D.docx?dl=0